Australian Government
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Manual of
AVIATION METEOROLOGY

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MANUAL OF AVIATION METEOROLOGY

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CHAPTER 14
MAJOR WEATHER SYSTEMS AND PATTERNS

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THE ATMOSPHERE

The atmosphere consists essentially of a mixture of gases. Within these gases tiny solid particles of dust and smoke are suspended. In addition, water occurs not only as a vapour, but also in solid and liquid forms.

1.1 The Composition Of The Atmosphere

The composition of dry air by volume at sea level at locations remote from large cities and forest fires is:

- Nitrogen 78%, Oxygen 21%, other gases 1%.

In general gases of the atmosphere are present in the same proportions up to an altitude of about 80 km. However there are some important exceptions such as water vapour, ozone and carbon dioxide. These gases are found in the following quantities in the lower levels of the troposphere:

- Water vapour 0 - 5%
Essential for cloud formation and is the main source of the greenhouse effect;

- Carbon dioxide 0.037%
Absorbs infrared (IR) radiation and contributes to the greenhouse effect;

- Ozone 0.001%
Toxic and very reactive. Low level ozone is the main gaseous constituent of airborne pollution.

Water vapour is the most important gas as far as meteorology is concerned. The amount of water vapour in the air (often expressed as relative humidity) varies greatly between the oceans and deserts, between ground level and higher altitudes, and between cold and hot regions. Even though water vapour makes up only a small percentage of the atmosphere, the energy released/consumed as it changes from gas to liquid to ice and back again,

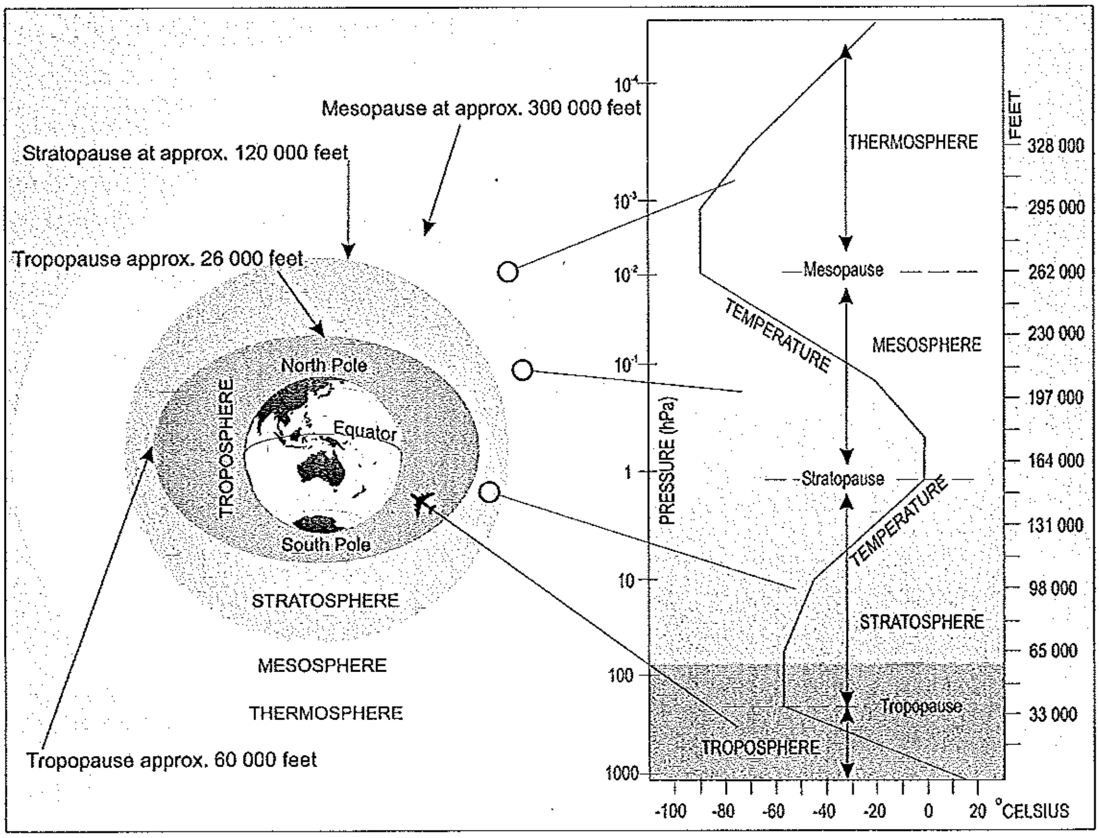


Figure 1.1
Divisions of the atmosphere, illustrating the variations of temperature with height.

drives many severe weather systems such as thunderstorms, tornadoes and cyclones.

1.2 Vertical Divisions Of The Atmosphere

The atmosphere can be divided into four layers based on the mean variation of temperature with altitude as depicted in Figure 1.1.

- *The Troposphere,* the lowest layer is deeper over the tropics than the poles. It is mainly heated from below by the earth's surface. Tropospheric temperature decreases with height. The upper boundary of the troposphere is known as the tropopause.
- *The Stratosphere* is heated by ozone that is concentrated between 50 000 feet (15 km) and 100 000 feet (30 km) above the earth's surface. The ozone absorbs heat from the sun. Temperature in the stratosphere increases slowly at first then more rapidly with altitude. The upper boundary of the stratosphere is known as the stratopause.
- *The Mesosphere* is a region of decreasing temperatures with height. The coldest region of the atmosphere occurs at the top of this zone. The upper boundary of the Mesosphere is known as the mesopause.
- *The Thermosphere* is characterised by rising temperatures with height.

1.3 The Troposphere

The troposphere contains most of the mass of the atmosphere. It is characterised by marked vertical air motions, appreciable water vapour, cloud and weather and is the region where most flights take place. Temperatures generally decrease with height in the troposphere but shallow layers in which the temperature increases with height often occur. Such layers are called temperature inversions.

1.4 The Tropopause

The boundary between the troposphere and the stratosphere is called the tropopause. Although Figure 1.1 depicts the tropopause as an oval shape the configuration is far more complex. Its altitude varies with latitude, the season and the movement of weather systems. The tropical tropopause typically exists at an altitude of 60 000 feet (18 km). At high latitudes the polar tropopause is

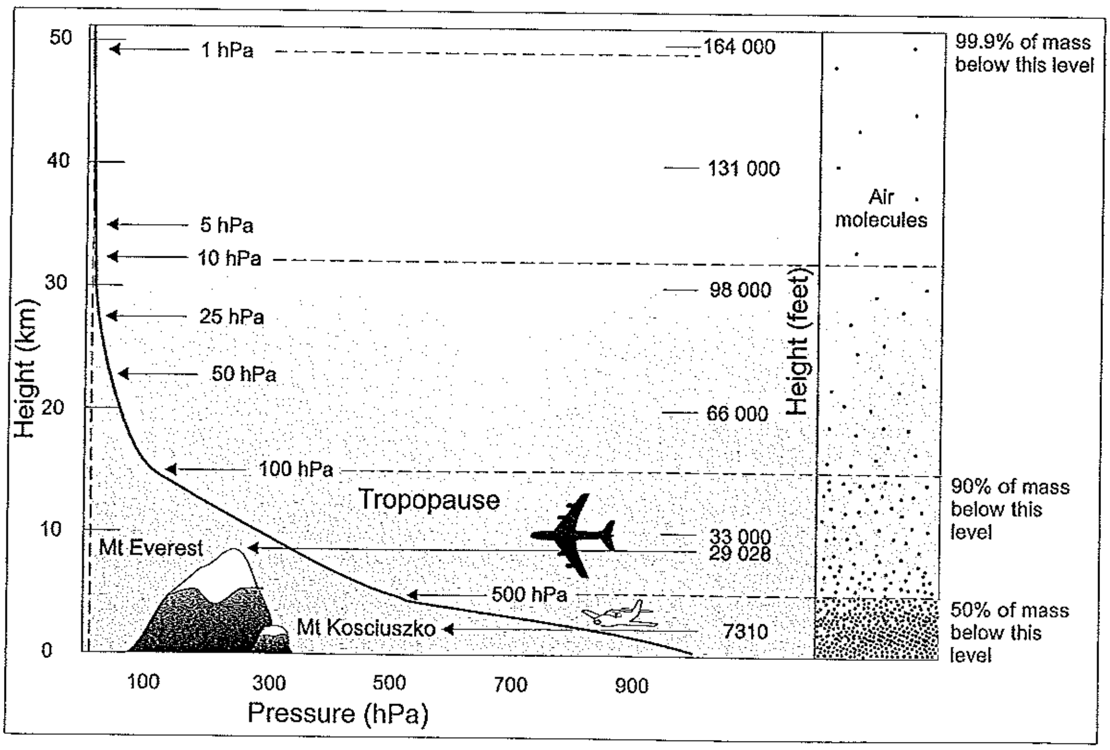


Figure 1.2
A cross section of the atmosphere illustrating variations of air pressure and mass with height.

found at approximately 26 000 feet (8 km). Between these two regions there is a sloping middle-latitude tropopause, with breaks and overlaps occurring in the vicinity of jet streams.

1.5 The Weight Of The Atmosphere

The pressure exerted by the atmospheric gases at any altitude depends on the weight of the air particles above that point. Figure 1.2 shows that the atmospheric pressure near mean sea level is about 1013 hectopascal (hPa) while at an altitude of 50 km the pressure is only about one hPa, indicating that only about one-thousandth of the mass of the atmosphere exists above 50 km.

Figure 1.2 shows atmospheric pressure decreasing more rapidly with height in the lower layers. At an altitude of 18 500 feet (500 hPa) one half of the atmosphere's molecules would already be below you. That is, half of the mass (weight) of the atmosphere is contained in the layer below 500 hPa.

1.6 The International Standard Atmosphere (ISA)

To enable comparison between aircraft heights over a wide range of meteorological situations the International Civil Aviation Organization (ICAO) has adopted an International Standard Atmosphere (ISA); it is a model atmosphere for which the average variation of temperature with height is specified. From this the corresponding variations of pressure and density can be deduced. It specifies a sea-level pressure of 1013.25 hPa and temperature of 15°C, with a fixed lapse rate for temperature of 1.98°C per 1000 ft up to 36 090 feet (the theoretical tropopause height of the ISA), where the temperature is assumed to be -56.5°C.

For practical purposes the ISA can be assumed to have sea level pressure of 1013 hPa at a temperature of 15°C and a lapse rate of 2°C per 1000 feet up to 36 000 feet with a corresponding temperature of -57°C.

The ISA is used for altimetry and as a reference for aircraft performance standards.

HEAT EXCHANGE PROCESSES

The transfer of heat energy from one region to another is the major influence on the world's weather and climate. The enormous amount of energy involved in this redistribution is apparent in the ferocity of tornadoes and cyclones and in vigorous frontal systems. It is also evident in the broad scale winds that sweep across the earth's surface.

2.1 Incoming Solar Radiation

The energy emitted by the sun is often called short-wave radiation because approximately 99% of the sun's energy is emitted in the shorter wavelengths. It is important to discriminate between different wavelengths because atmospheric processes, which are driven by radiation are often strongly influenced by wavelength.

The percentages of the total energy emitted in various wavelengths from the sun are:

- 9 % in the ultraviolet wavelengths;
- 45 % in the visible;
- 46 % in the near infrared.

Of this radiation, on average:

- 20% is absorbed in the atmosphere by clouds and gases;
- 31% is reflected back to space;
- 49% is absorbed by the earth's surface (sunny day 75%, cloudy day 15%).

Most of the ultraviolet (UV) radiation is absorbed by ozone in the stratosphere while water vapour in the lower atmosphere absorbs much of the near infrared radiation. Very little of the visible radiation is absorbed. Clouds and dust, can absorb varying amounts depending on prevailing conditions. Some of the radiation reaching the earth's surface is also reflected away. Solar radiation may also be scattered in all directions by gases and particles in the atmosphere. Some of this scattered radiation is lost to outer space, and some is scattered back to the earth's surface. Solar radiation reaching the earth indirectly by scattering is called sky radiation. Thus the total radiation reaching the earth's surface consists of direct radiation and sky radiation, and is known as global solar radiation.

2.2 Outgoing Terrestrial Radiation

Just as the sun emits energy due to its temperature, the earth too, emits energy called terrestrial radiation. Because the earth is much cooler than the sun, the terrestrial radiation emits in that part of the electromagnetic spectrum known as long-wave radiation.

The atmosphere is less transparent to long-wave radiation than it is to the short-wave radiation leaving the earth's surface, with 90% being absorbed. Substances that absorb only small amounts of solar radiation, for example carbon dioxide, water vapour and clouds, are significant absorbers of terrestrial radiation.

Efficient absorbers of radiation are also good emitters of radiation, for example clouds absorb terrestrial radiation from the earth's surface. They also emit long-wave radiation some returning back to the earth's surface and some to space.

2.3 Radiation Balance And Heat Exchange

The earth radiates energy to space constantly but only the daylit side of the earth receives incoming radiation. On the dark side of the earth there is a net loss of radiation occurring, whereas on the daytime side there is a net gain by the earth-atmosphere system. Overall, a heat balance is maintained.

This balance does not usually apply at specific latitudes. Due to the angle of the earth's surface to the sun, latitudes near the equator receive more energy than latitudes near the poles. In fact between the equator and 35° north and south more energy is absorbed than is radiated to space. There is an energy surplus in this region. Similarly, an energy deficit occurs in regions between latitude 35° north and south and the poles.

If there were no exchange of heat between different latitudes, areas near the equator would get hotter and hotter while areas near the poles would continue to cool, leading to an increasing meridional (from equator to pole) temperature gradient. What actually occurs is a transfer of heat from low to high latitudes by means of atmospheric and oceanic circulations.

This north/south transfer of heat occurs through a number of processes. Large-scale eddies in the atmosphere (high and low-pressure systems) transfer heat between tropical and polar regions by the movement of cold air equatorward and warm air poleward. Ocean currents also carry heat energy away from tropical regions towards the poles.

The redistribution of the sun's energy within the atmosphere can occur through the following processes:

- conduction — transfer of energy by contact, through molecular motion;
- advection — energy transferred by the horizontal movement of air;
- convection — energy transferred by the vertical movement of air;
- latent heat — absorption and release of heat energy through evaporation, freezing and condensation of water;
- radiation — transfer of energy by electromagnetic waves (short and long).

Conduction

Thermal conduction is an efficient means of transferring heat through solid materials but is poor for gases. In the atmosphere it is important in transferring heat to air in direct contact with the earth. These layers are usually only a few centimetres thick.

Convection

Thermal convection lifts heat away from the surface of the earth (having been heated by conduction). Rising air forms currents often referred to as thermals. The thermals not only transport sensible heat aloft; they also transfer upwards latent heat stored in water vapour. Convection is responsible for the formation of cumulus clouds.

Advection

Advection of heat occurs most notably with the horizontal movement of large air masses. Australians living south of the tropics will be well aware that in general summer northerly winds bring hot conditions while wintertime southerly winds are cold.

Latent heat

Water molecules are strongly bound together in both the solid and liquid state but in the gas state, bonds are weak. A change from liquid water to water vapour requires the bonds to be broken, taking an enormous amount of heat energy.

To appreciate the energy required to break the strong bonds that hold water together consider this: it takes 4.2 joules of heat energy to raise the temperature of a gram of water by 1°C at standard temperature and pressure, but to change the gram of water (without increasing the temperature) into water vapour requires takes 600 times more energy to break the bonds than it does to raise the temperature of water by 1°C.

The heat energy used to break the bonds is absorbed by the water vapour. The absorbed heat maintains separation of the molecules, required for the gas state. Because the energy is absorbed and effectively stored within the molecules, it is called latent heat. Thus water vapour transports large amounts of latent heat energy from one region to another.

When water vapour condenses latent heat is released into the surrounding air, thus warming it. The warmer, less dense air becomes buoyant and rises. It is the warming power of latent heat that powers precipitating weather systems, e.g. thunderstorms, tropical cyclones and snowstorms.

Figure 2.1 illustrates the phase changes of water and the amount of latent heat released and absorbed during those changes. Note that the heat energy required to break the molecular bonds of ice for a phase change to water (80 units) is much less than that required to achieve a phase change of water to water vapour (600 units).

Frost is formed by deposition, when water vapour changes directly to ice (releasing 680 units of energy). The same process occurs in the freezing compartment of a refrigerator.

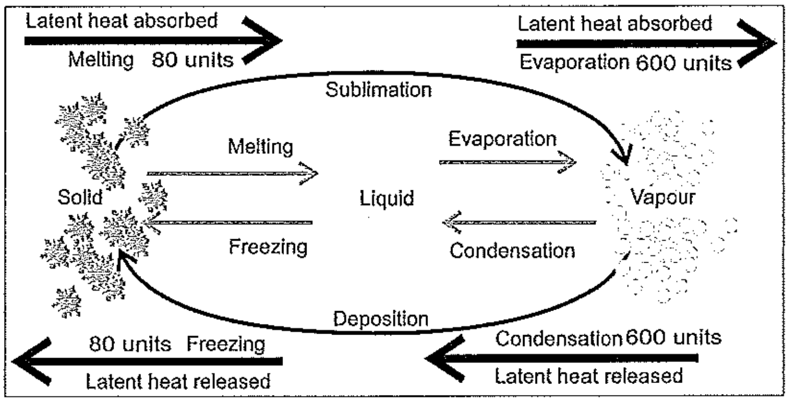


Figure 2.1
The diagram shows the phase changes of water, melting, evaporation, condensation, freezing, sublimation and deposition. It also shows the quantity of latent heat absorbed and released by changes of state. Note that when ice sublimates directly to water vapour the total latent heat absorbed will be 680 units.

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.

3.1 MEASURING TEMPERATURE

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.

Temperature scales common to aviation 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. To convert from one to the other use the following formulae:

- C = 0.555 (F-32)

e.g. to convert 95°F to °C:
C = 0.555 (95-32) = 35°C

- F = (1.8 x C) + 32

e.g. to convert 35°C to °F:
F = (1.8 x 35) + 32 = 95°F

Many flight computers provide direct conversion of temperature from one scale to the other.

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.

3.2 SURFACE AIR TEMPERATURE

For meteorological purposes, surface air temperature is the temperature of the air measured 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 or a system of metal shields with forced ventilation (often used with Automatic Weather Stations (AWS)).

3.3 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.

3.4 AIRCRAFT MEASURED TEMPERATURE

The aircraft temperature probe measures's outside air temperature (OAT) – sometimes referred to as the static air temperature (SAT). However, when in flight, the effects of friction and compression, result in the indicated temperature being significantly higher (warmer) than the actual OAT. The indicated temperature is referred to as the total air temperatures (TAT) and has to be corrected to obtain the true OAT.

3.5 Diurnal Variation Of Surface Air Temperature

The change in surface temperature from day to night is referred to as the diurnal variation. During the twenty-four 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 largely 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.

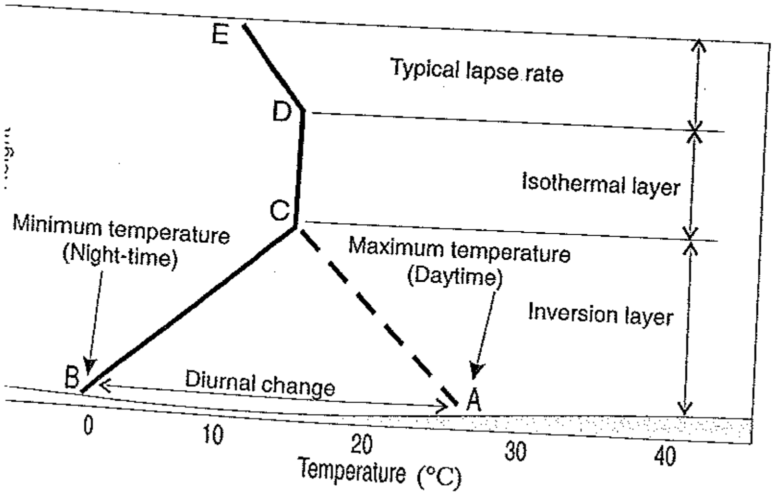


Figure 3.1
Diurnal variations of temperature in the vertical. Temperature near the earth's surface may vary greatly between A and B nainly due to conduction etween the ground and ir in contact with it. The iagram also illustrates an sothermal layer DC, an version BC, and a normal pse rate ED where mperature decreases with titude.

3.6 Temperature Variation In The Vertical Within The Troposphere

As already mentioned in Chapter 1, the temperature decreases with altitude in the troposphere at about 2°C per 1000 feet (6.5°C per kilometre). This means that, 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.

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, i.e. 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 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.

4.1 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:

$$D = \frac{P}{RT}$$

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.

4.2 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.

4.3 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 4.1.

4.4 Density Altitude

Density altitude is the pressure altitude (the standard height of a pressure level in the ISA) corrected for temperature deviation from the ISA. It is computed from the pressure altitude and the outside air temperature.

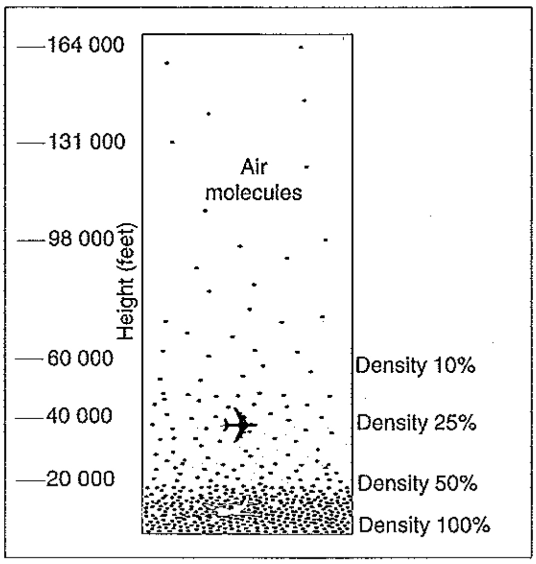


Figure 4.1
The diagram illustrates the rapid decrease of density with height.

Aircraft performance deterioration resulting from low air density can occur when there are large deviations between the ISA altitude and the density altitude. This most often happens at elevated aerodromes when the air temperature is high. Low air pressures accentuate the problem.

The following incident reports from the Australian Transport Safety Bureau (ATSB) illustrate that density variations must be taken into account, especially on hot days.

Incident 1

Sequence of events

While the pilot was conducting the takeoff from Fossil Downs Station, the environmental conditions may have changed such that the power required to maintain the helicopter's departure profile exceeded the power available from the engine. As a result, the main rotor RPM decayed and the helicopter descended onto the ground.

The pilot had not adequately assessed the power needed to conduct the takeoff and had used an inappropriate takeoff technique for the environmental conditions and helicopter weight. There was a misunderstanding between the operator and the customer as to the use of the helicopter. The pilot inadvertently believed he was authorised in accordance with the company operations manual to conduct the passenger flights. The helicopter's operator was unaware that the passenger flights were being conducted.

Significant factors

1. The pilot was inexperienced.
2. The density altitude and relative humidity were high.
3. The wind conditions were gusty.
4. There was no documented data or guidance available to the pilot to assist him in assessing the expected performance of the helicopter during the takeoff.
5. The pilot did not adequately plan the takeoff to account for the weather conditions and helicopter landing site characteristics.
6. The pilot used an inappropriate takeoff technique.
7. The helicopter was probably at or close to maximum all up weight and had inadequate performance to complete the takeoff in nil wind.
8. The weather conditions had changed since the first takeoff and did not assist the helicopter during the second takeoff.

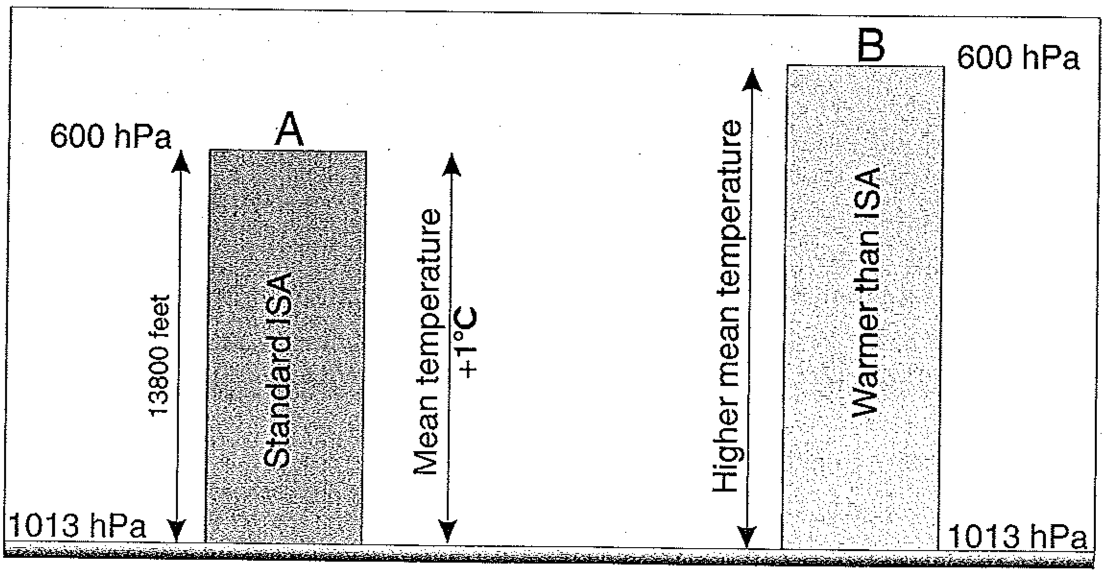


Figure 4.2
Two air columns having the same surface pressure but with different densities. The less dense (warmer) column is higher because less dense air requires greater depth to produce the same surface pressure.

Incident 2

Sequence of events

The aircraft took off from runway 30 and began climbing at a shallow angle, which a witness reported was below the normal climb profile. When the aircraft reached a point about 100 m beyond the upwind threshold of the runway, the tower controller informed the pilot of inbound traffic directly ahead of the aircraft. At that time, the tower controller also noticed that the aircraft was exhibiting 'wobbles' and became concerned for its safety. Witnesses reported that the aircraft slowly climbed to about 300 ft and then seemed to lose altitude. The aircraft then continued tracking outbound in a shallow climb on runway heading, before the right wing dropped. The aircraft then rolled to the right, assumed a steep nose-down attitude and began rotating. After one turn, the aircraft impacted the ground in a steep nose-down inverted attitude. A fireball engulfed the aircraft immediately after impact. The four occupants received fatal injuries.

An instructor assessed the pilot's flying skills as sound, but added that the pilot tended to be over-confident. Another instructor said that although the pilot's aircraft handling met the required standard, he tended to be casual and to chat during flight. He added that the pilot did not always concentrate sufficiently on the task in hand, and did not always prepare fully for cross-country flights.

Aircraft performance

According to performance charts, the aircraft was capable of takeoff and climb from runway 30 with 15 degrees of flap selected, and climb at maximum gross weight under the prevailing environmental conditions. However, with a density altitude of 3400 feet and the aircraft gross weight just below MTOW, the pilot would have needed to monitor take-off and climb performance closely.

Environment

The density altitude of 3400 ft and the aircraft's gross weight (just below the maximum permitted) combined to adversely affect the aircraft's acceleration and climb performance. This was evident from the witness reports stating that the aircraft's angle of climb seemed to be shallower than normal for single-engine light aircraft departing on runway 30. The brief loss of altitude before the right wing dropped was probably the result of the pilot raising the flaps.

As the aircraft was lower than the normal climb profile, rising terrain ahead might have affected the pilot's assessment of the aircraft's nose attitude with respect to the horizon or its rate of climb with respect to terrain, leading him to select a higher nose attitude than he would have selected otherwise.

In warmer than standard temperature conditions the density altitude will be higher than the standard pressure altitude. This means that the aircraft performance will be the same as if it were operating at a higher altitude. Consider a column of air (Figure 4.2) conforming to the ISA, with a density decrease with height coincident with standard temperature and pressure. Now consider another column with the same surface pressure of 1013 hPa but with a higher than standard mean temperature. The second column must be less dense than the 'standard ISA' column (A) because of a higher mean temperature.

Aircraft performance at the same altitude will be less in column B conditions than in column A even though the surface pressure is the same. The reduction in performance is due to lower 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.

High density altitudes are a particular problem in Australia during summer. Some extreme values for Australian aerodromes are shown in Table 4.1. 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.

Table 4.1
Some extreme values of observed density altitude in Australia.

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

4.5 Density/Temperature and Altimetry

Altitude indicated by altimeters depends on density (thus temperature) beneath the aircraft. Since altimeters are graduated to the standard atmosphere any variation in temperature from standard will cause altimeters to indicate higher or lower than actual altitude (Figure 4.3).

As an approximation, an atmosphere 10°C colder than the ISA requires the altitude to be lowered by roughly 4% to give the true altitude, i.e. at an indicated altitude of 5000 feet in temperatures 10°C colder than ISA - true altitude would be 4800 feet.

Pilots have met with disaster because they failed to allow for the differences between indicated and true altitude. In cold weather when you must clear high terrain, take time to compute true altitude (FAA, Aviation Weather).

NOTE: Refer to the guide for Visual Flight Rules (VFR) for detailed altimetry information.

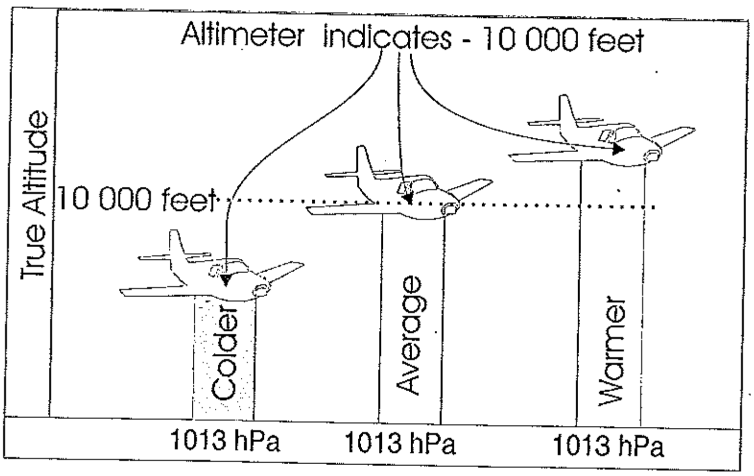


Figure 4.3
Indicated altitudes depends on air temperature below the aircraft. Each column in this diagram has equal pressure at top and bottom, indicated altitude is the same for each aircraft. In ISA (average) conditions the altimeter indicates actual altitude (centre column), higher than actual altitude in colder/denser air (left column) and in warmer/less dense air lower than actual altitude (right column).

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.

5.1 The Measurement Of Atmospheric Pressure

Two main types of barometer are used to measure atmospheric pressure, the mercury-in-glass and the aneroid barometer. The mercury barometer was traditionally more accurate but considered fragile and cumbersome to transport. Aneroid barometers are more compact and rugged and for this reason are more commonly used. Modern digital aneroid barometers are proving extremely accurate and reliable. Aneroid cells are used in altimeters.

5.2 Variation Of Pressure With Altitude

The rate of pressure decrease with altitude is not linear (as shown in Figure 5.1). 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

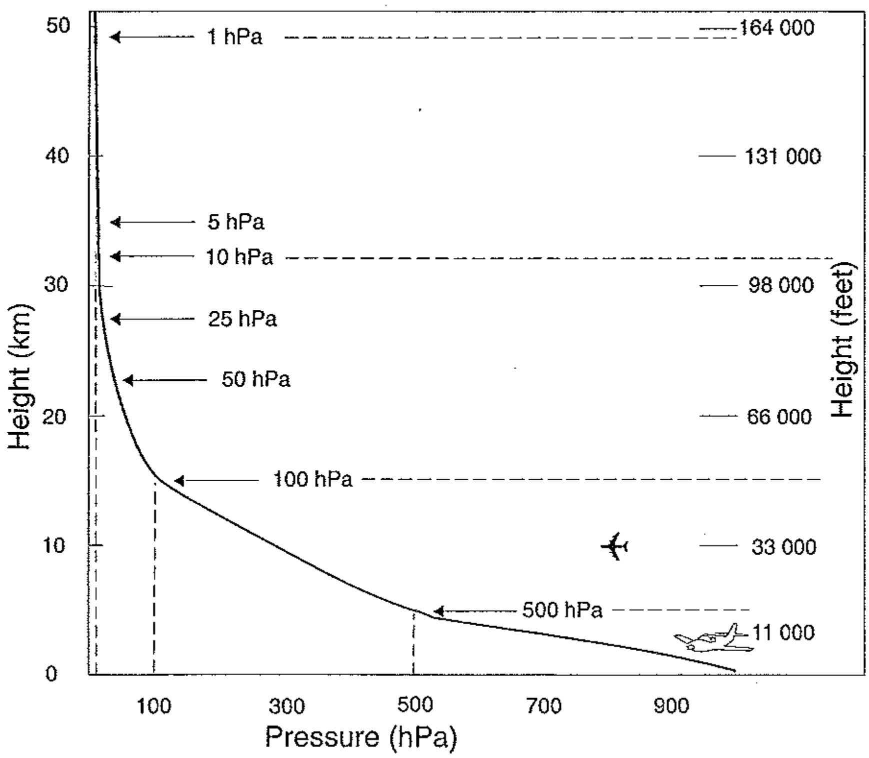


Figure 5.1
Variation of pressure with altitude in the standard atmosphere.

because of the impact of temperature variations.

5.3 Adjustment Of Recorded Pressure To Standard Levels

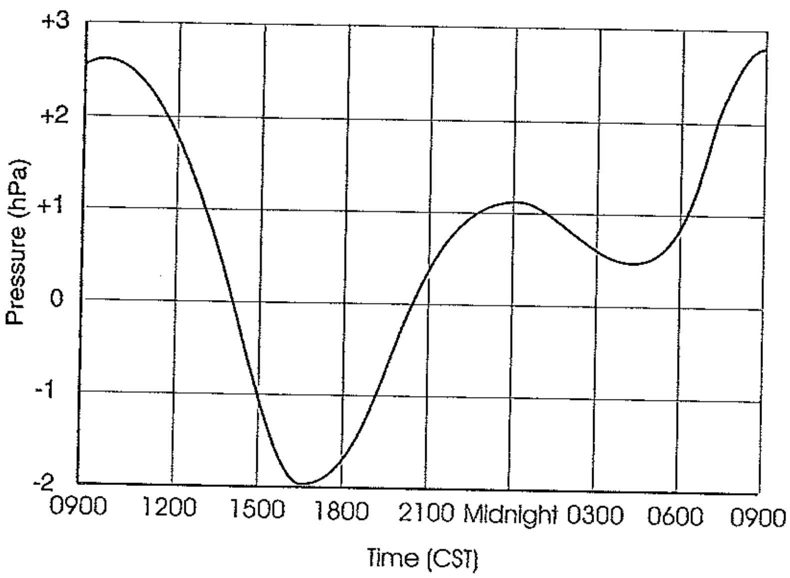
To compare station level pressure (SLP) at different elevations, it is necessary to reduce the recorded pressure to mean sea level (MSL) pressure.

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.

In parts of Africa and Antarctica the elevation of meteorological stations is well above one kilometre. These stations, after obtaining SLP, compute the approximate altitude at which 850 0r 700 hPa pressures occur above them. Synoptic weather charts are then drawn at these levels.

Figure 5.2
Regular pressure variations for Darwin during September, with a period of about twelve hours.



5.4 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.

In the tropics, the diurnal variation of pressure is more evident than in higher latitudes. Figure 5.2 illustrates the diurnal pressure variations (about 5 hPa) for a typical September day at Darwin, Australia.

5.5 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 5.3 showing tightly spaced isobars around a low-pressure system near Perth indicative of a strong-pressure gradient and strong winds while well separated isobars around a high pressure system centred near Adelaide are indicative of a weak-pressure gradient and light winds.

5.6 The Pressure Altimeter

Before we go further, a clear definition of the following terms (illustrated in Figure 5.4) 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.

The pressure altimeter operates on the principle that pressure decreases with height.

The pressure altimeter is basically an aneroid barometer calibrated to read heights above a specified pressure datum.

5.7 Pressure Values And Altitude

Because aircraft performance specifications are often given in terms of ISA conditions (Section 1.6) actual atmospheric conditions are sometimes expressed in terms of ISA deviation. For example, if the ISA temperature at 36 000 feet is -56°C and if the actual temperature at a pressure altitude of 36 000 feet was -52°C, this would be expressed as 'ISA plus 4'.

Apart from being a reference for aircraft performance standards, the main use of the ISA is for calibrating aircraft altimeters so that pressure values are converted to altitudes by a standard internationally agreed method.

5.8 Altimeter Settings

1013 hPa – The mean sea level pressure of the ISA

With this setting, the altimeter display will indicate the aircraft altitude, in the ISA atmosphere, above the 1013 hPa level. This is the pressure altitude. Pressure altitudes are generally quoted in hundreds of feet and called flight levels. In aviation weather forecasts the prefix FL is used to denote flight levels. For example, the pressure altitude of 12 500 feet is FL125.

QNH – An altimeter set to QNH will read zero at sea level. In flight the QNH will indicate the approximate altitude above sea level. This is the pressure value given in all meteorological forecasts and observations and in the Automatic Terminal Information service (ATIS).

QFE – 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. This setting is calculated by adjusting the SLP to the aerodrome reference level, assuming ISA conditions. QFE is not used in Australia but may be used in some other countries.

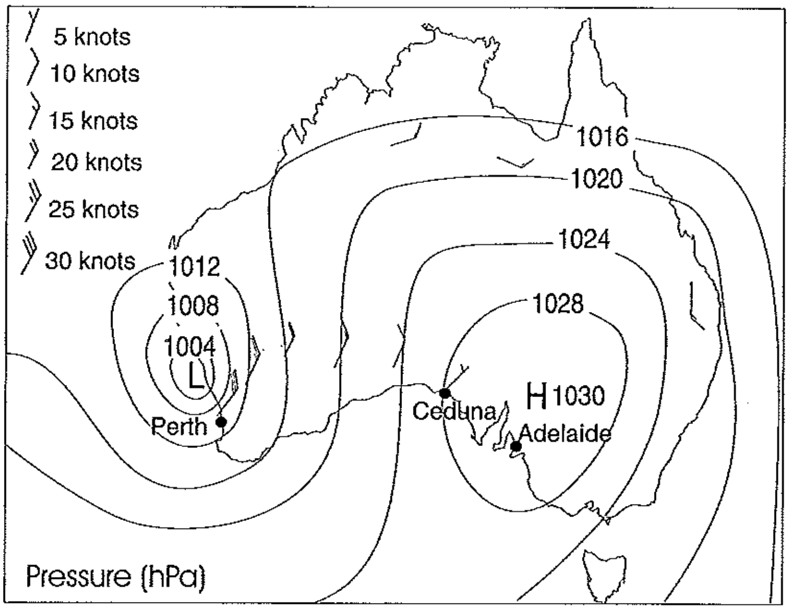


Figure 5.3
Isobar spacing and wind speed. Wind barbs are shown crossing the isobars into the region of low pressure. The wind near Perth is from the north-northeast (NNE) at 30 knots while the wind near Ceduna is from the northeast at 5 knots.

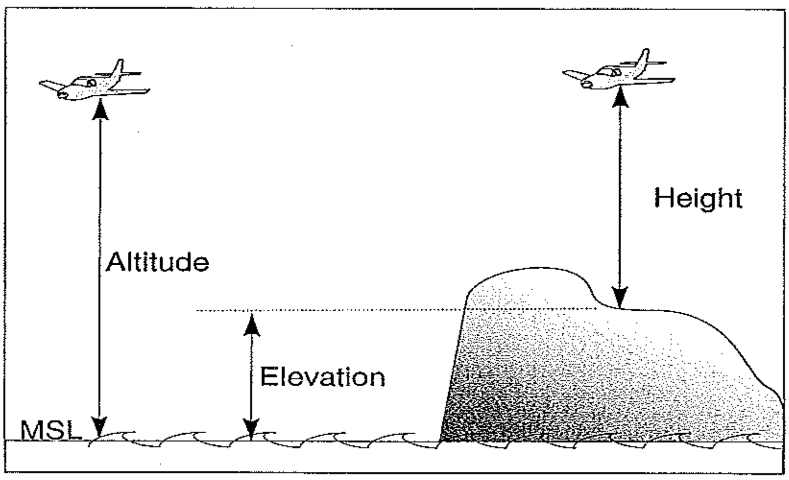
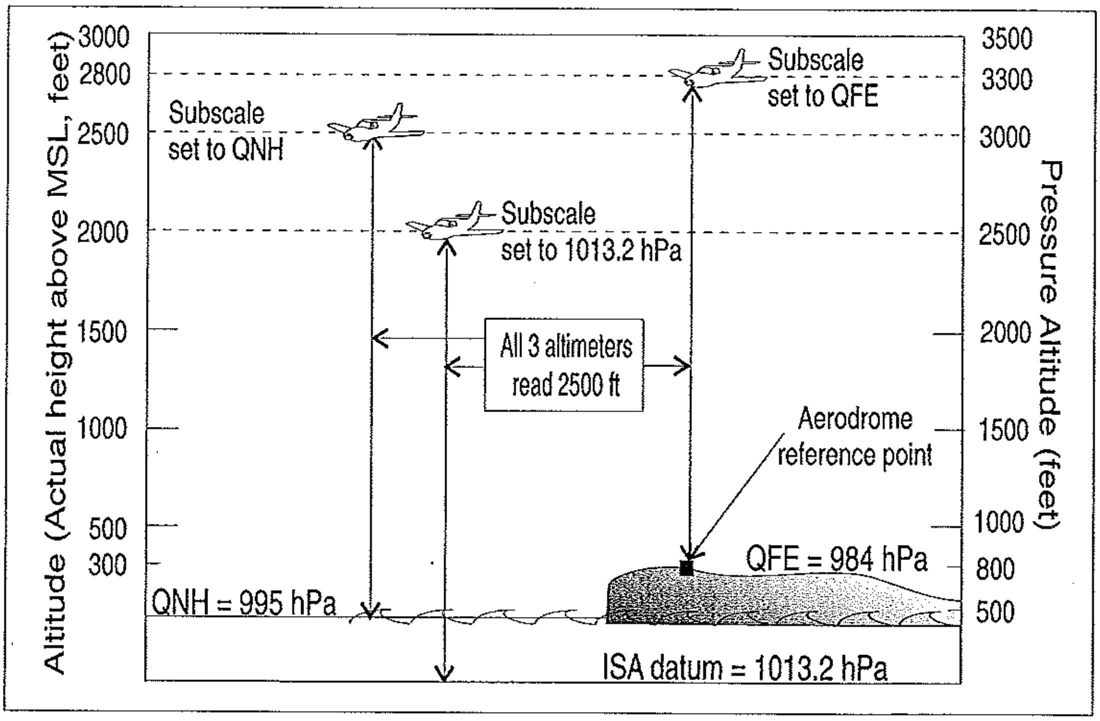


Figure 5.4
Altitude, elevation and height

Figure 5.5
Shows three aircraft with altimeter subscales set to QFE 984 hPa, QNH 995 hPa, and to 1013.2 hPa. The left-hand scale indicates the actual height of the aircraft above sea level while the right hand scale indicates the pressure altitude (the altitude indicated by the altimeter). All three aircraft altimeters indicate 2500 feet.



Examples of different altimeter settings are shown in Figure 5.5.

A guide for calculating altitude changes with respect to pressure changes in the standard atmosphere is:

- the average change from the surface to about 12 000 feet is 30 feet per hectopascal;
- the average change between 12 000 and 20 000 feet is 43 feet per hectopascal.

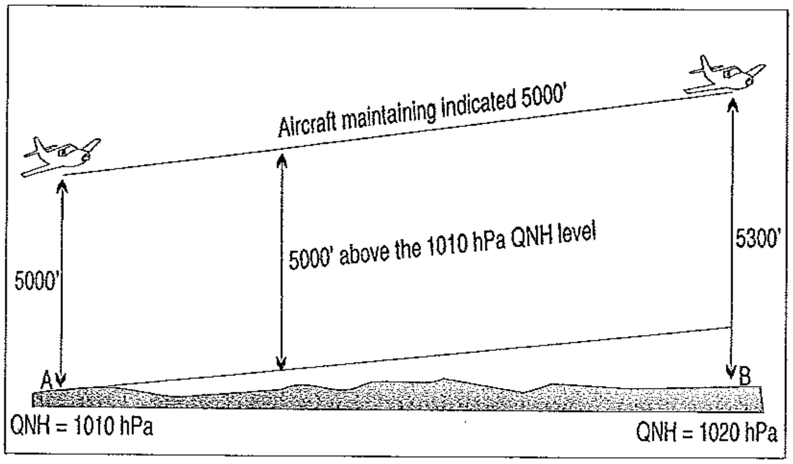
5.9 Flying With Changing Ground Pressures

If a constant altimeter reading is maintained then the aircraft must be following a constant pressure surface. But pressure surfaces usually slope so the aircraft will be descending when flying towards lower surface pressures, and ascending when flying towards higher surface pressures.

Consider the following example illustrated in Figure 5.6. An aircraft flying at 5000 feet above A, sets QNH at 1010 hPa. The aircraft flies to B where QNH is 1020 hPa. The altimeter will indicate that the aircraft is still at an altitude of 5000 feet but the aircraft will actually be 300 feet higher.

Alternatively, an aircraft flying above B at 5300 feet sets QNH at 1020. This aircraft would arrive at A with the altimeter still reading 5300 feet but be 300 feet lower then indicated.

Figure: 5.6
Changing ground pressure alters altitude of aircraft flying on a set QNH.



5.10 Localised Pressure Variations

Sometimes purely local effects can give a pressure change of two to three hPa with consequent effect on the altimeter reading of up to 100 feet.

An example of such an effect is a low-pressure trough in the lee of high terrain. The air movement up and over the terrain causes a pressure reduction immediately in the lee. A strong wind flow will produce a greater effect. Thunderstorms are another source of comparatively large, localised pressure variations

VERTICAL STABILITY OF THE ATMOSPHERE

Vertical motion of air is an important factor in the development of weather. Sometimes rising air is made visible by the development of clouds or by the rising dust in dust devils. Violent vertical motion can be seen in tornadoes. At other times rising air may occur in the absence of any visual clue. Subsiding air is normally relatively gentle and associated with clear conditions (except in association with mountain waves and downburst activity from convective clouds).

The strength of vertical motion in the atmosphere is largely determined by the vertical stability of the atmosphere. A stable atmosphere will tend to resist vertical motion, while an unstable atmosphere will assist it. When the atmosphere neither resists nor assists vertical motion it is said to have neutral stability.

Vertical motion and instablity are largely responsible for atmospheric turbulence and cloud formation.

6.1 Adiabatic Processes And Lapse Rates

To explain the stability or instability of the atmosphere, we consider here what happens to an imaginary 'parcel' of air displaced vertically from one level to another. The parcel will expand when it moves to lower pressure (higher altitude) and contract when it moves to higher pressure (lower altitude).

During displacement it is assumed the parcel undergoes an adiabatic temperature change, i.e. no heat from the external environment is added or subtracted. Adiabatic heating is demonstrated when using a bicycle pump. Compression heats the air and thus the outer casing of the pump. The reverse occurs when air escapes from a tyre. It cools due to rapid expansion.

Accurate measurements of heating or cooling during these processes are difficult because some mixing normally occurs with air outside the parcel, and heat may also be lost or gained through radiation. However, these examples are very useful in explaining how the atmosphere behaves.

The rate of change of temperature with height for a vertically displaced parcel of air is termed the adiabatic lapse rate. Two different lapse rates apply: the dry adiabatic lapse rate (DALR) and the saturated adiabatic lapse rate (SALR).

The DALR is the rate at which the temperature of unsaturated air changes as a parcel ascends or descends through the atmosphere. The DALR is approximately 3°C/1000 feet. In other words until air becomes saturated, it behaves like dry air.

The SALR is the rate at which the temperature of a parcel of air saturated with water vapour changes as the parcel ascends or descends. The SALR is often taken as 1.5°C/1000 feet, although the actual figure varies according to the amount of water vapour present and also the temperature (higher temperature air can contain more water vapour).

The SALR is less than the DALR because as a parcel of saturated air ascends and cools the water vapour condenses into water droplets, releasing latent heat into the parcel, thus slowing the cooling. Conversely if a saturated parcel descends and warms, latent heat is absorbed from the parcel, thus reducing the rate of warming (generally termed evaporative cooling).

6.2 Determining Stability

Air rises if it is warmer than its surroundings. Technically air doesn't rise because it is warmer; it rises because warm air is less dense than cold air, and thus more buoyant.

If the vertical temperature distribution of an air mass is known, the rate of change of temperature with height can be determined and thus the stability.

The atmosphere is considered to be stable, unstable, neutral or conditionally unstable as follows:

- if, because of the vertical temperature distribution (lapse rate) a lifted parcel is cooler and therefore denser than the surrounding air, the parcel will tend to sink. Thus the environment is defined as being **stable**;
- if because of the vertical temperature distribution a lifted parcel is warmer and less dense than the surrounding air, the lifted parcel will continue to rise. In this case the environment is defined as being **unstable**;
- if the lapse rate is such that a lifted parcel is the same temperature as the surrounding air, conditions are said to be **neutral**;
- in some situations the atmosphere is stable for unsaturated parcels of air but unstable if saturated. This is called **conditional instability.**

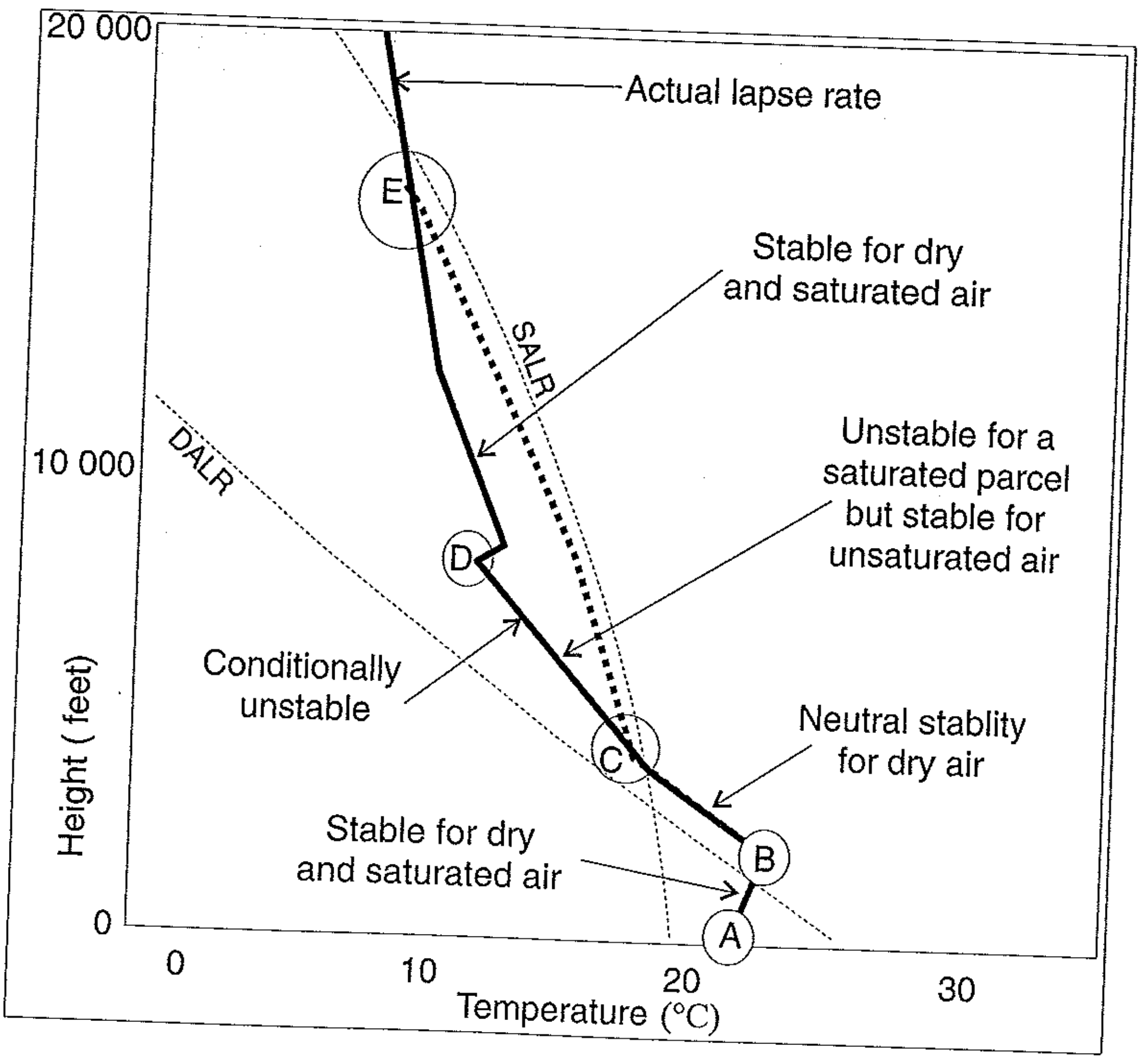


Figure 6.1
A temperature altitude graph, with the lapse rate displayed by a thick black line. In the layer A to B the temperature increases with height, as it does in the layer immediately above D. Elsewhere the temperature decreases with height. DALR and SALR lines are depicted as thin dotted lines. The thick dashed line depicts the displacement of a saturated parcel rising from C to E, along the SALR.

Referring to Figure 6.1, stable, unstable, neutral and conditionally unstable layers can be determined by comparing the temperature lapse rates (black line) with the DALR and the SALR:

- any parcel (dry or saturated) forced to rise and cool at the DALR or SALR, between A and B will remain cooler than the environmental temperature and would therefore sink once forcing had ceased. The layer is said to be **stable**;
- a parcel forced to rise and cool through the **neutrally stable** layer between B and C at DALR will continue to rise only if forcing continued, because it would be neither warmer or cooler than the environment;
- any saturated parcel rising through the **conditionally unstable** layer from C to D at SALR would remain warmer than the environment and thus continue to rise and cool at the SALR. On the other hand, an unsaturated parcel would cool at the DALR, remain cooler than the environment and sink once any forcing had been removed;
- like the layer from A to B, all parcels, saturated or unsaturated rising between D and E would only continue to rise if they were forced upward, since the layer is **stable.**

In general when the environmental lapse rate:

- is between the DALR and the SALR the atmosphere is considered to be conditionally unstable;
- is less than the SALR the atmosphere is considered to be absolutely stable;
- is the same as the DALR it is considered to be neutrally stable;
- is greater than the DALR it is considered to be absolutely unstable.

6.3 The 'SkewT-LogP' Aerological Diagram

The Australian Bureau of Meteorology mainly uses the 'SkewT-LogP' aerological diagram to determine stability.

Although an understanding of the aerological diagram is not a pre-requisite for pilots, it is discussed here because such diagrams are freely available over the internet and are used extensively by glider pilots to calculate thermal activity. The diagrams are also useful for a better understanding of the changes that occur in the atmosphere on a daily basis.

The diagram's name reflects the parameters associated with the vertical and horizontal axes. Atmospheric pressure (hPa) is plotted along the vertical axis using a logarithmic scale. This represents the variation of atmospheric pressure with height observed in the earth's atmosphere. The pressure scale is along the left-hand side of the diagram. Temperature (0°C) is shown along the horizontal axis, increasing from left to right. The lines of constant temperature are 'skewed' from the lower left to the upper right of the chart.

The diagram is used for determining the stability of the atmosphere above a specific location by comparing the actual lapse rate with the DALR and SALR lines (thin dashed lines discussed later) on the chart. The stability is of interest in relation to rising air parcels, because if the atmosphere is unstable and moist, showers or thunderstorms may be a consequence, depending on the magnitude and depth of instability and moisture availability. Rain occurs when the atmosphere is moist but stable, and there is a mechanism for continuous lift.

Since the pressure and volume of the rising parcel will change according to the lower pressure encountered higher in the atmosphere, the temperature and dew-point will also change. If it is known how much these parameters change we can predict if the parcel will be warmer or cooler than the actual lapse rate and thus the stability of the parcel can be determined. For this reason dashed lines of dry adiabats, moist adiabats and mixing ratio are displayed on the diagram. A parcel will rise parallel to one of the lines depending on whether it is unsaturated or saturated. The dew-point will follow the mixing ratio lines (dew-point decreases about 0.6°C per thousand feet) to the level of saturation. Thus:

- *dry adiabat lines* depict the DALR. They represent the path for an unsaturated parcel of air;
- *moist adiabat lines* depict the SALR. They represent the path for a saturated parcel of air;
- *mixing ratio lines* depict the dew-point rate of change (and the path) for an unsaturated air parcel (Dew-point temperature is the temperature a parcel of air would have to be cooled to, for it to become saturated).

A parcel will generally subside (sink) along a dry adiabat, undergoing compressional warming and quickly becoming warmer than the surrounding air and hence becoming stable.

6.4 Temperature Inversions

Temperature inversions are of interest because:

- they generally limit vertical development of clouds;
- they trap pollutants that reduce visibility;
- noticeable changes in aircraft performance sometimes occur when flying through them;
- turbulence is frequently encountered when flying through and/or near inversions.
- fog and low cloud often form in light winds, within low-level inversions, when moisture levels are high.

Three common causes of temperature inversions in the lower atmosphere are:

- radiation from the earth's surface;
- subsidence (sinking air) associated with high pressure systems;
- frontal systems.

Subsidence, radiation and frontal inversions are evident in the Perth soundings in Figure 6.2.

For the latest sounding (red line):

- a radiation inversion exist from the surface to about 980 hPa;
- a frontal inversion lies just above 600 hPa.

For the previous sounding (blue line):

- a subsidence inversion existed near 800 hPa.

Other features to note in the figure are:

- the tropopause for the latest (red) sounding is near 360 hPa;
- the tropopause for the previous sounding (blue) was near 410 hPa.

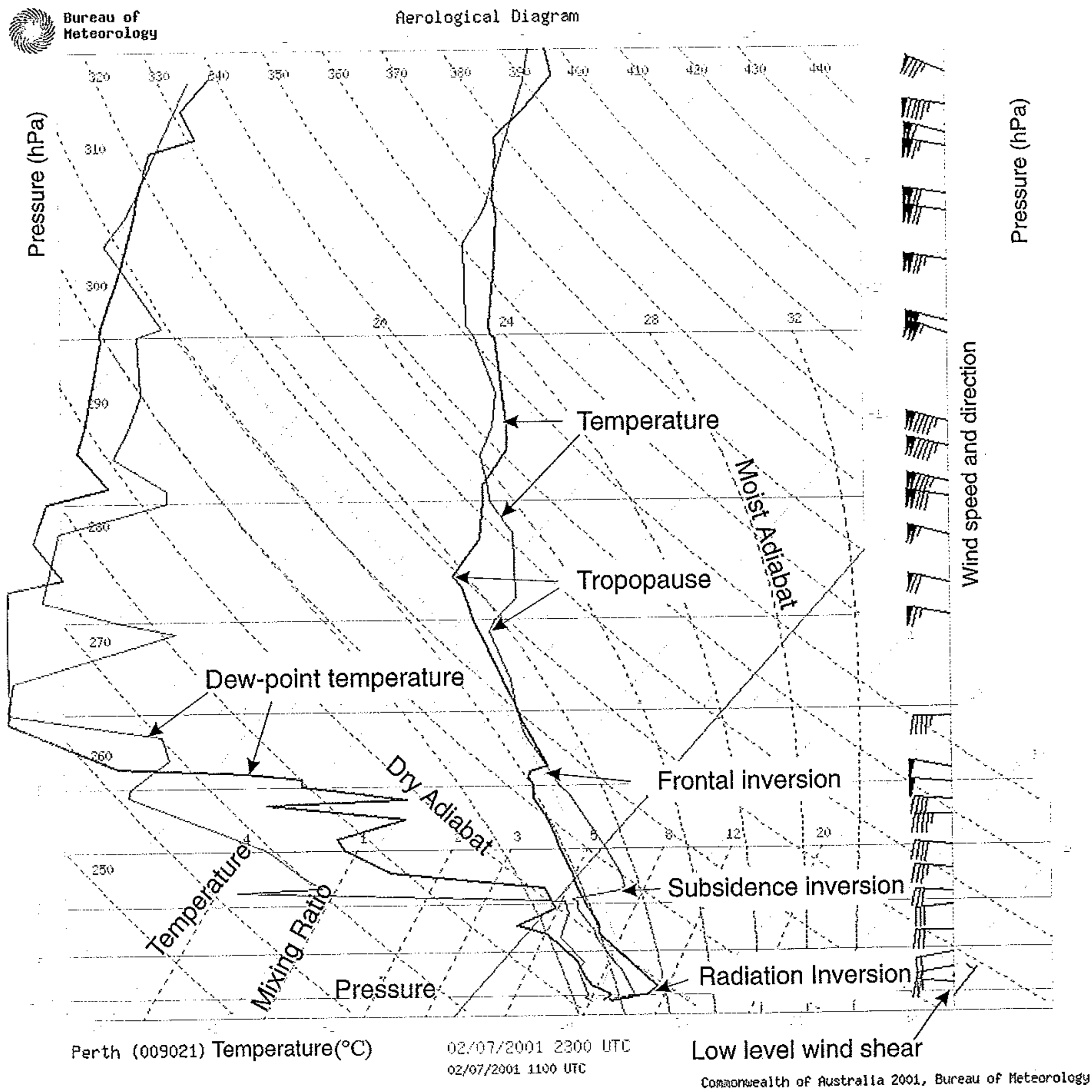


Figure 6.2

Shows two separate sets of temperature and dew-point temperature plots. The red plot is for 02/07/2001 at 2300 UTC and the blue plot is for 02/07/2001 at 1100 UTC. The two plots show changes in temperature and moisture, and from this can be inferred changes in the stability during a twelve-hour period. The barbs on the right-hand side show the variation in wind direction and speed (knots) with height for the time of the latest plot. Solid triangles represent a wind speed of 50 knots; a single line represents 10 knots while a half line represents 5 knots. So at 400 hPa the wind is 65 knots while at 200 hPa it is 155 knots. The wind direction is plotted to the compass, i.e. at the surface the wind is a northeasterly while at 600 hPa it is a westerly. Note the light and variable wind in the surface inversion layer (northeast at 5 knots) compared to above the inversion (westerly at 20 knots) indicative of significant wind shear of approximately 25 knots at the top of the inversion. Also note that winds increase with height to a maximum of 155 knots near 200 hPa.

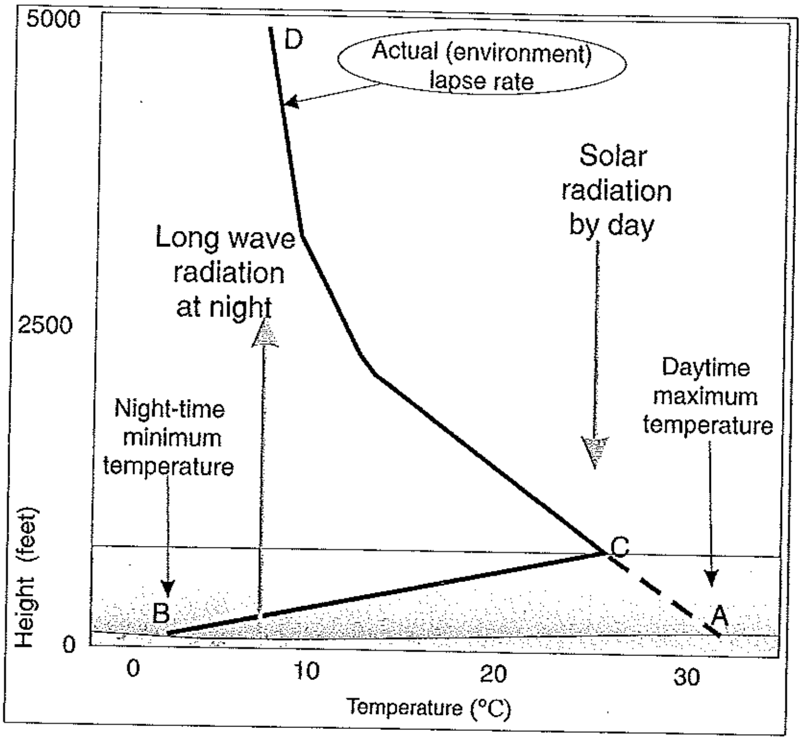


Figure 6.3
A temperature altitude graph showing the lapse rate at the time of surface minimum temperature, as a thick black line, BCD. The line ACD represents the lapse rate at the time of surface maximum temperature. Layer BC is the inversion layer.

Surface radiation inversions
Surface inversions form on clear, light-wind nights and are strongest around sunrise. They form as air in contact with the ground cools by conduction. Because air is a poor conductor, strong surface inversions tend to be shallow, typically a few hundred feet thick, and can occasionally have a temperature increase with height of up to 10°C from the surface to the top of the inversion. Deeper radiation inversions may extend many hundreds of feet if light turbulent winds mix the very cold surface air into the warmer air above. Figure 6.3 shows the structure of a radiation inversion with a shallow layer of cold air under warmer air.

The rapid decrease in density associated with strong surface radiation inversions can have a noticeable affect on climb performance, especially for light aircraft.

Surface inversions can also be associated with strong wind shear when the less dense air at the top of the inversion tends to flow over the colder air, rather than mixing with it. An aircraft climbing through the top of an inversion may experience a sudden increase in wind speed and/or direction and turbulence.

Within the inversion layer visibility may be reduced by trapped particles of smoke and dust. Fogs are prone to form within radiation inversion layers.

Subsidence inversions
Subsidence inversions (depicted in Figure 6.4) frequently occur with high-pressure systems that cause air in the upper levels to sink and thus warm. When the upper layer warms at a greater rate, an inversion is formed. A typical subsidence inversion in the Australian region occurs at an altitude of 4000 to 6000 feet. Subsidence inversions are strongest and lowest on the eastern flank of high pressure systems.

Subsidence inversions can be of significance to aviation because:

- thick haze and smoke can be trapped beneath the inversion so that descent through the inversion is coincident with markedly reduced visibility;
- convective currents are inhibited so that low-level convective clouds are limited in their vertical development. Cloud tops therefore spread out below the inversion layer to form a solid layer of stratus or stratocumulus cloud. With slow moving high-pressure systems this cloud layer may persist for several days especially during winter (sometimes referred to as anti-cyclonic gloom);
- persistent low stratus cloud may form, if surface conditions are moist and light winds mix the air to saturation below the inversion;
- they provide ideal environments for fog because:
  - the atmosphere is generally clear above the inversion;
  - winds below the inversion are light;
  - pollutants are trapped within the inversion layer providing an abundance of condensation nuclei;
  - humidity is often high;
  - conditions are favourable for radiation inversions to form below a subsidence inversion.

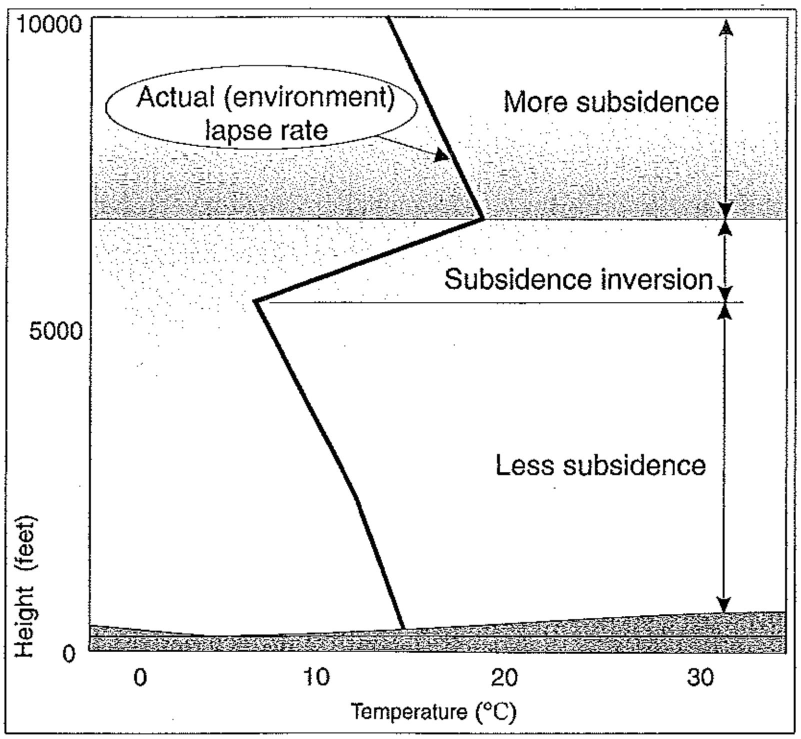


Figure 6.4
A temperature altitude graph typical of a subsidence inversion. The lapse rate (shown as a thick black line) shows high-level warm air overlying low-level cooler air. The demarcation zone between the warm and cool air is referred to as the subsidence inversion.

Frontal inversions

Frontal inversions (depicted in Figure 6.5) form at the frontal surface in the upper atmosphere between the cool and warm air separating two air masses. Similar inversions occur on a more local scale at the sea breeze front. The inversion itself is not as significant to aviation as the weather that accompanies it. However turbulence and wind shear typically occur at the interface zone between cooler and warmer air that may upset smooth flight.

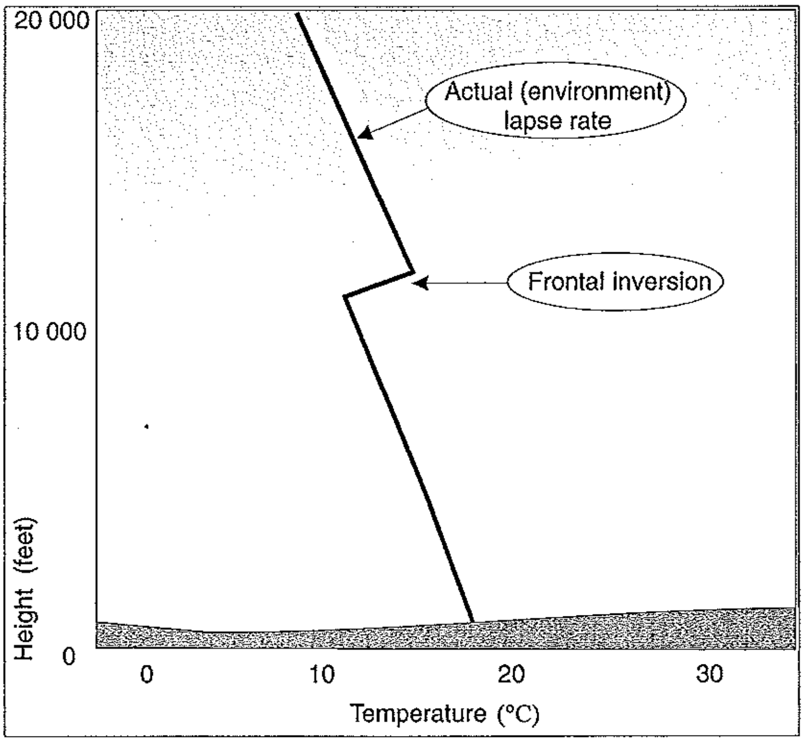


Figure 6.5.
A temperature altitude graph showing the lapse rate as a thick black line depicting a frontal inversion at upper levels.

CLOUD

An appreciation of cloud types and formation processes can alert pilots to associated phenomena significant to aircraft operations.

A cloud is a visible aggregate of tiny water droplets and/or ice crystals suspended in the atmosphere and can exist in a variety of shapes and sizes. Heavy precipitation, severe winds, turbulence and aircraft icing accompany some clouds.

8.1 Cloud Classification

There are ten main cloud types, categorised as low, middle or high according to the height of the cloud base. These are listed in Table 8.1.

8.2 Cloud Height

Cloud base heights are reported in feet. Typical base heights above mean sea level are listed in Table 8.1. Under hot inland conditions the bases of cumulonimbus and cumulus clouds may be observed at even higher levels than those stated in the table. Note: height of cloud bases for:

- ARFOR (ARea FORecast) are above mean sea level;
- TAF (Terminal Area Forecast) are above aerodrome elevation;
- METAR/SPECI observations are above aerodrome elevation.

8.3 Cloud Formation

Cloud formation requires significant amounts of water vapour, adequate condensation nuclei and a cooling mechanism to bring air to saturation.

The most efficient way to cool air is by lifting it to higher altitudes. Ascent may be initiated when:

- air warmer than its environment becomes buoyant and rises (convection);
- air is forced to flow up and over higher terrain (orographic);
- air is forced to rise over frontal surfaces (widespread ascent):
- winds converge at low levels (sometimes widespread but can be local).

If the rising air is warmer than the surrounding atmosphere and condensation occurs, a cumuliform type of cloud is produced. If the rising air remains cooler than the surroundings atmosphere and condensation occurs, cloud formation is

HIGH	Cirrus	Ci	20 000 to 40 000 ft
	Cirrostratus	Cs	
	Cirrocumulus	Cc	
MIDDLE	Altostratus	As	8500 to 20 000 ft
	Altocumulus	Ac	
	Nimbostratus	Ns	From 500 to 8500 ft, sometimes up to 20 000 ft
LOW	Cumulonimbus	Cb	From 2000 to 5000 ft, sometimes down to 1000 ft or up to 10 000 ft
	Cumulus	Cu	
	Stratocumulus	Sc	2000 to 5000 ft, sometimes down to 500 ft or up to 8000 ft
	Stratus	St	500 to 2000 ft, sometimes just above the surface and up to 4000 ft

Table 8.1
Cloud classification and typical base heights above mean sea level.

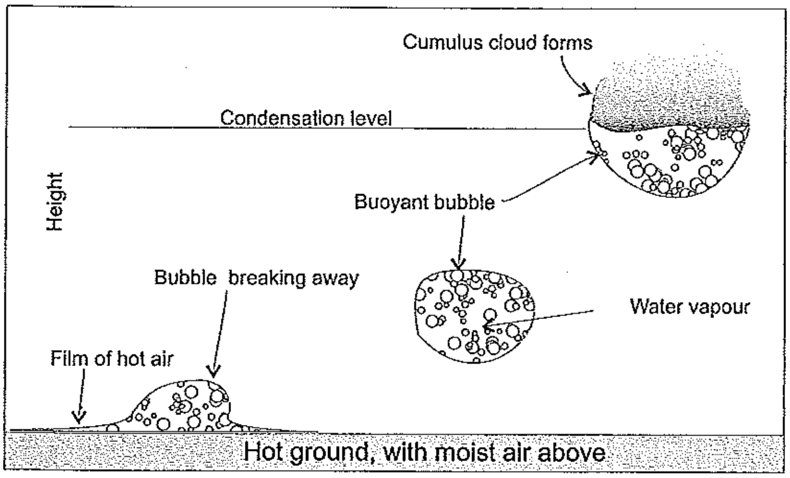
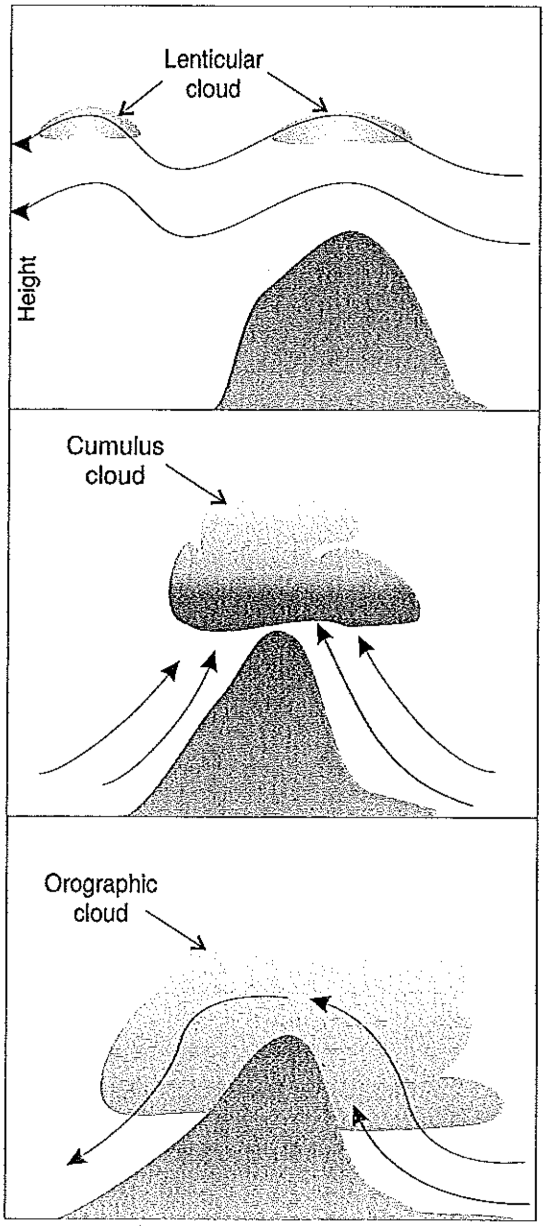


Figure 8.1

Ascent of a buoyant air bubble. Initially a film of very hot air is established over the ground. Breakaway bubbles of air occur over hot spots.

Figure 8.2

Three examples of cloud formation due to the lifting of moist air.



stratiform. Two other important mechanisms for cooling air are:

- the mixing of warmer air with cooler air (turbulent mixing);
- air contacting cooler surfaces (conduction).

Convective ascent

Air will rise from the surface by convection when bubbles of surface air are heated more than their surroundings as illustrated in Figure 8.1. Suitable conditions commonly occur when:

- strong surface heating occurs during the day:
- a relatively cold air stream moves over a warmer surface.

Cumuliform clouds may form if the surface air is moist enough and by rising, the air is cooled to saturation. The depth of convection is determined by the moisture content of the rising air and the temperature distribution of the environmental air.

Buoyant bubbles carry with them moisture that will condense to form cloud if it reaches the condensation level.

Orographic ascent

Orographic ascent is the forced vertical motion of air by mountains or raised terrain. The type of cloud formed depends on the stability of the atmosphere and moisture content of the surface layer. Some examples of cloud formation are depicted in Figure 8.2.

Orographic cloud forms on higher ground when moist air condenses below the ridge-top in stable conditions. Cumulus clouds form when air flowing over high terrain condenses above the hilltops when the atmosphere is unstable. Lenticular clouds form above hilltops when wave motion in the atmosphere lifts moist air to saturation in a generally stable atmosphere. In the lenticular case, cloud forms in the up motion section of the wave and dissipates in the downward flow past the wave. It is the wave formation that creates the lens shape of the lenticular cloud.

Widespread ascent

Widespread ascent frequently occurs when one air mass slides up and over another. This may occur with the slow convergence of air from a region of high pressure to a region of low pressure. Widespread ascent also occurs in the frontal zones and within troughs of low pressure. Figure 8.3 illustrates the clouds that may form if the lifted air is moist enough, namely stratus (St), cumulus (Cu), cumulonimbus (Cb), altocumulus (Ac), when a mass of cold air forces warm moist air to be lifted. The cold air acts like a wedge.

Turbulent mixing

Air flowing over terrain is generally deformed by frictional forces into a series of eddies similar to water in a fast flowing stream. Strong low-level inversions have the capacity to contain the turbulence in a confined layer, leading to cooler air from the base of the inversion mixing with warmer air from near the top of the inversion, effectively cooling the entire layer. If at some point within the layer saturation occurs, stratus or stratocumulus cloud may form. Figure 8.4 depicts the formation of cloud by mixing air to saturation below an inversion.

At higher levels some forms of altocumulus as well as cirrocumulus occur in the turbulent region between two horizontal air currents moving from different directions or at different speeds.

Low ragged stratus clouds may form below cumulonimbus and nimbostratus through the process of turbulent mixing.

Conductive cooling

Contact cooling (conduction) is primarily responsible for the formation of dew, fog and frost. Dew will form when temperature falls to the dew-point and winds are so light that turbulent mixing does not occur. Fog is more likely to occur when winds are light but sufficiently strong to promote turbulent mixing of shallow saturated air. Fog formation is discussed in detail in Chapter 13.

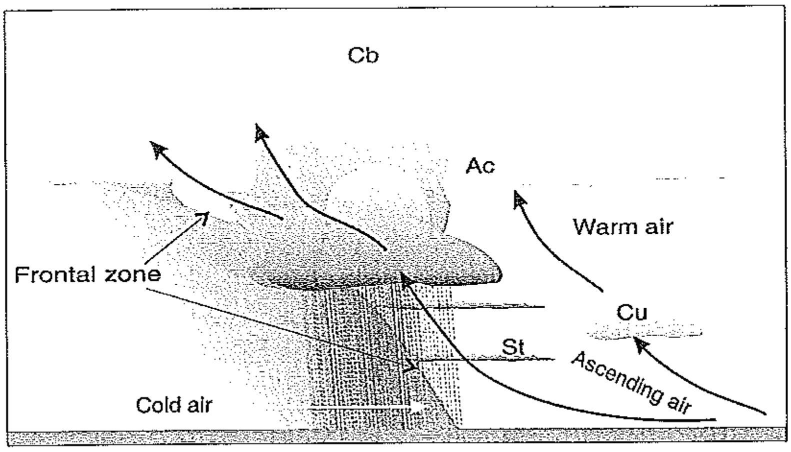


Figure 8.3
Widespread ascent associated with an active cold front. Moist air is lifted at the frontal zone and cooled to saturation. If the saturated air is buoyant, cumulus clouds form. If buoyancy can be maintained through a considerable depth of the troposphere then thunderstorm clouds (Cb) will form.

8.4 Cloud Base And Tops

Three calculated examples of cloud base and tops are included here to assist in understanding some cloud formation processes.

In Chapter 7 (section 7.5) a method for approximately calculating cloud base was given using dew point, temperature and the DALR. Meteorologists use aerological diagrams to carry out these calculations graphically. A detailed description has been given in Chapter 6.

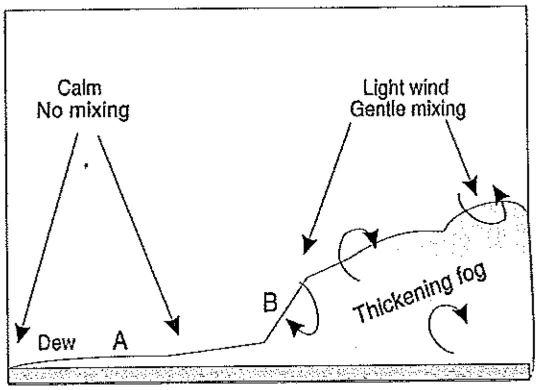


Figure 8.5
Contact cooling (conduction) of a shallow layer of air leading to saturation and the formation of dew in calm wind conditions (A). Light winds (B) promote mixing of cool air to higher levels, bringing a thicker layer of air to saturation, thus fog forms.

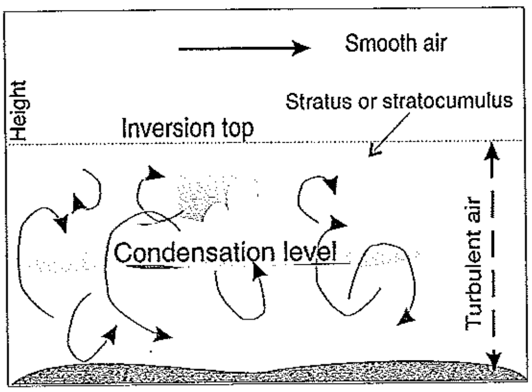


Figure 8.4
Air trapped beneath an inversion mixed by the wind results in cloud development below the inversion top.

Figure 8.6
This diagram uses the same format as the aerological diagram discussed in Chapter 6. The actual temperature lapse rate is depicted as a thick black line. For surface conditions of temperature 24°C and dew-point temperature of 12°C, a lifted parcel will saturate near 5000 feet. Thus the cloud base would form at this level. The saturated air would be free to rise (as it is buoyant) to the equilibrium level where it spreads out to form an anvil, typical of thunderstorm clouds.

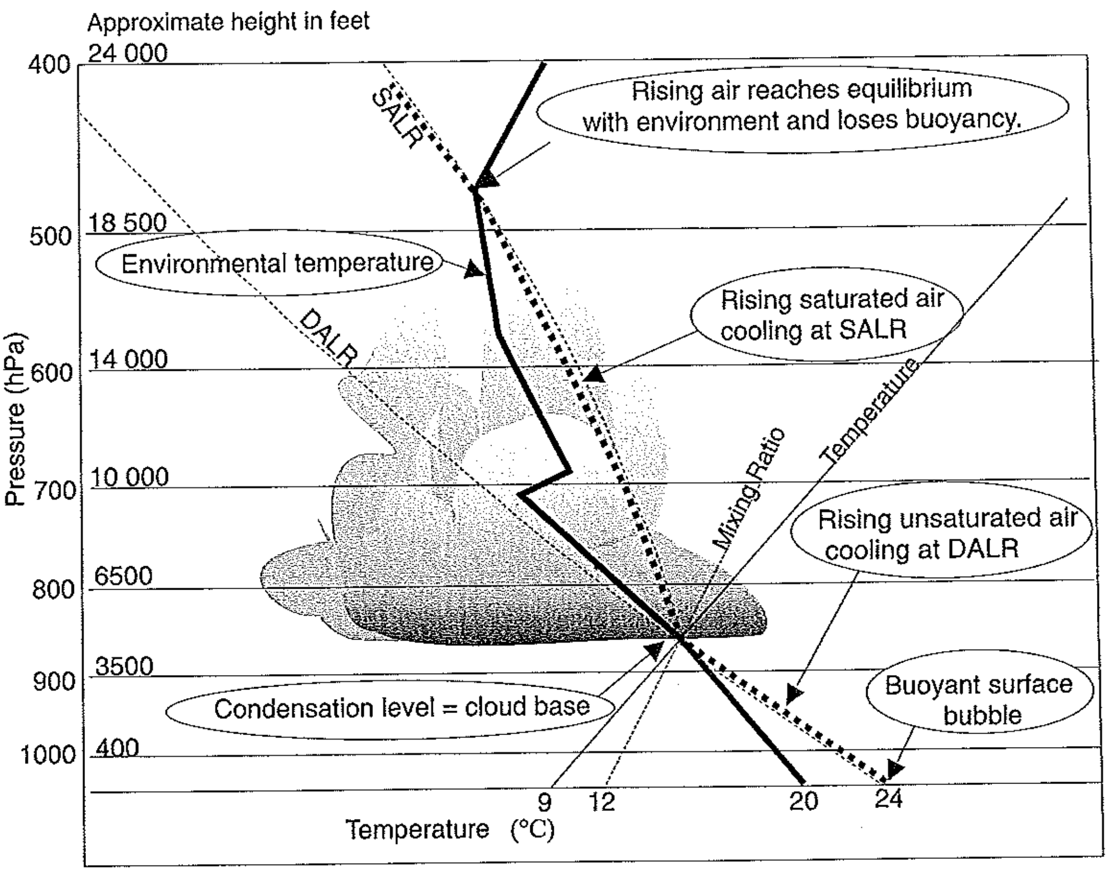
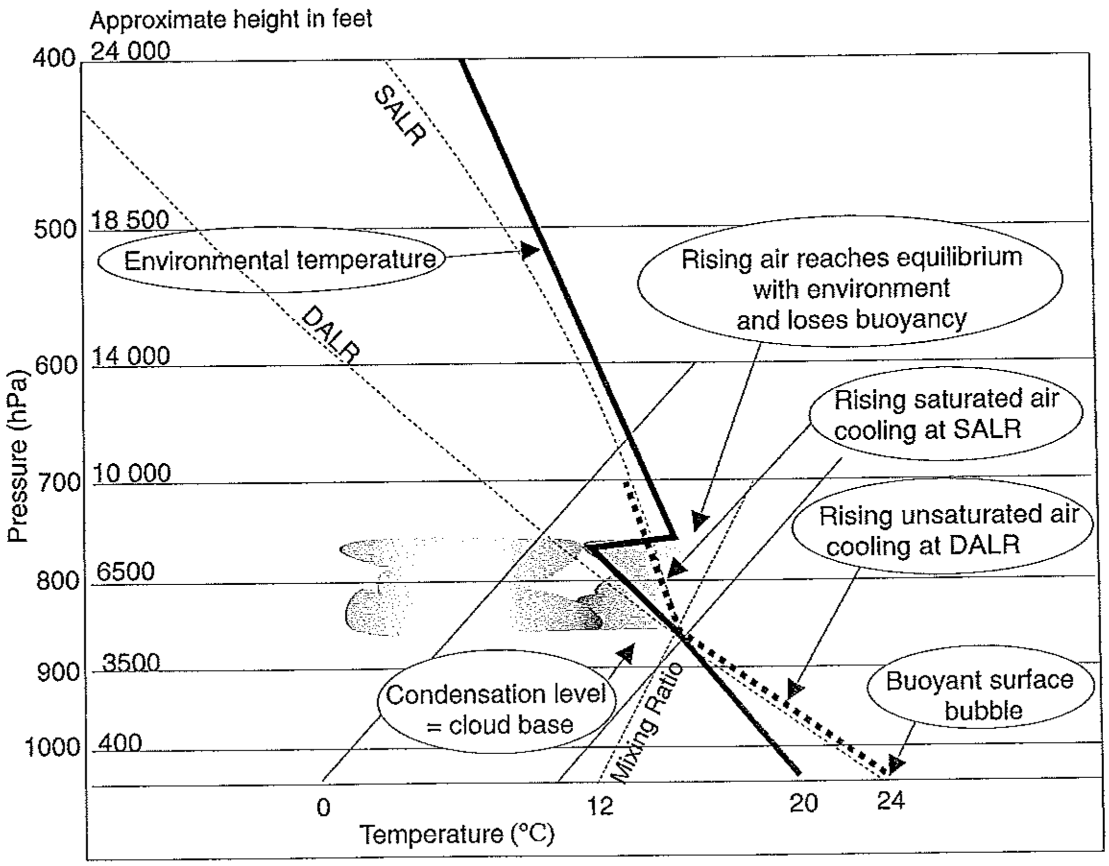


Figure 8.7
The actual lapse rate, shown as a thick black line, depicts a substantial inversion above a conditionally unstable layer (see section 6.2). For surface conditions of temperature 24°C and dew-point temperature of 12°C, a lifted parcel will saturate near 5000 feet. Cloud base would be at this level. The convective cloud would grow until it encounters the inversion. It then flatten out to form stratocumulus cloud.



If the temperature and humidity profiles of the atmosphere are known, we can determine, using stability considerations:

- whether cloud will form if air is lifted;
- the type of cloud that is likely to form;
- the height of cloud base and tops.

Convective ascent

For convection to occur a saturated parcel lifted from the surface must be warmer than the temperature of the surrounding environment. Using Figure 8.6 as an example, with a surface temperature of 20°C an air parcel forced to rise and cool at the DALR would remain cooler than the environment and thus it would tend to sink. However when the surface temperature reaches 24°C the parcel will rise and cool at the DALR to about 5000 feet and be cooled to 9°C. The original dew-point of 12°C will now be 9°C (0.6°C per 1000 feet), thus saturation occurs. The saturation level is represented on the diagram as the condensation level; it represents the cloud base. Further lifting will cause the parcel to cool at the SALR (along a path following the heavy dashed line). Because the parcel is now warmer than the environment it will be buoyant and free to rise until it reaches the equilibrium level where it becomes cooler than the environment.

The development of cumulonimbus cloud is frequently halted by the tropopause inversion, resulting in a massive and often spectacular anvil top.

If cumulus development is capped by a strong subsidence inversion the rising cumulus cloud will spread out into a deck of stratocumulus cloud as depicted in Figure 8.7.

Forced ascent

Forced ascent may occur:

- when air flows up mountain slopes (orographic ascent);
- when air is forced to rise in the vicinity of cold or warm fronts;
- when air converges at lower levels of the atmosphere, usually into regions of low pressure.

In the following example (Figure 8.8) surface air is forced to ascend over a range of hills or a cold front.

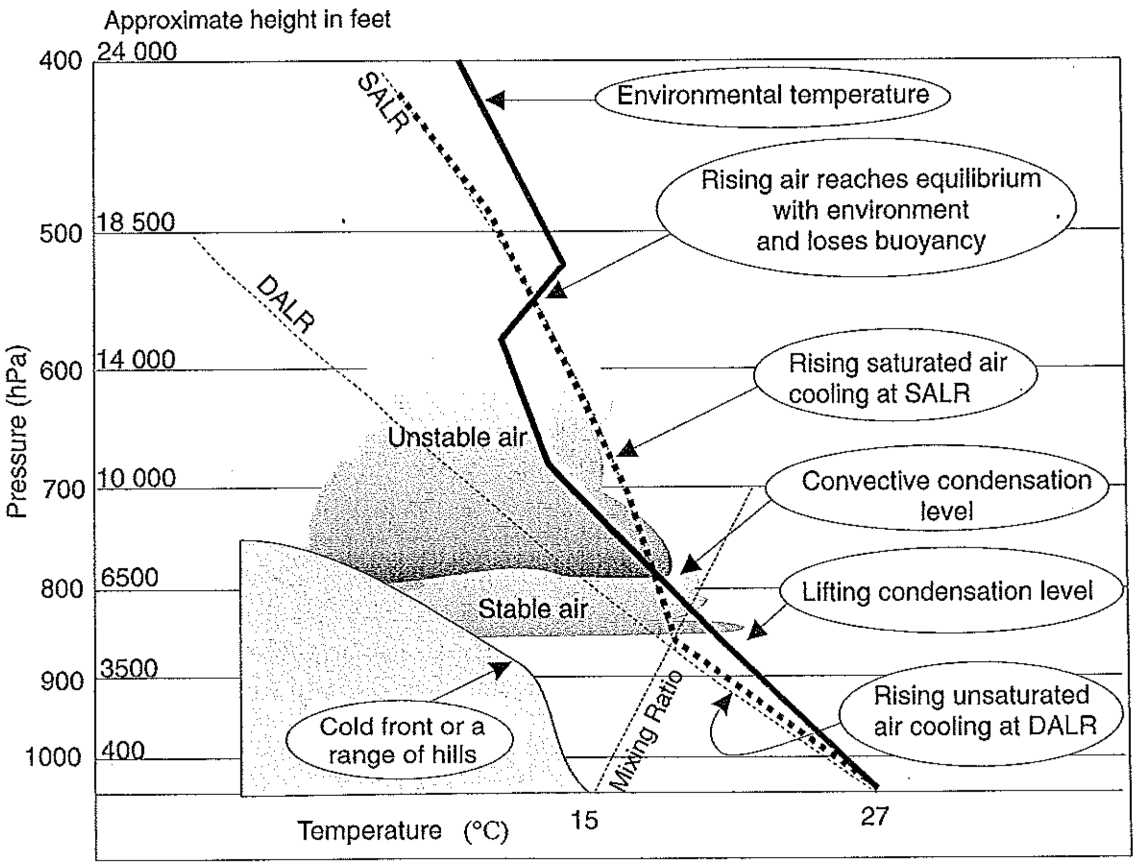


Figure 8.8.
A barrier such as a cold front or a range of hills is depicted along with the actual lapse rate of the air being forced over the barrier (the thick black line). For surface conditions of temperature 27°C and dew-point temperature of 15°C, air lifted from the surface will saturate near 5000 feet (temperature and dew-point temperature 12°C). The stratus cloud base would form at this level. With further lifting the air parcel would remain cooler than the environment up to about 7000 feet. Any further lifting would be at the SALR. Thus the air will be buoyant above 7000 feet. Convective cloud then is free to grow to the equilibrium level.

The previous examples are approximate because they assume the rising parcel of air does not mix with the surrounding air, whereas some mixing of environment air usually occurs. Turbulent mixing is ignored, as well as interactions between downdrafts and updrafts. Furthermore, vigorously rising air often does not stop suddenly when it reaches the same temperature as the environment (equilibrium level). With vigorous convection the overshooting tops may go beyond the equilibrium level by a few thousand feet.

8.5 Cloud Composition

Cloud droplets

Droplets initially form when water vapour condenses onto minute particles called condensation nuclei, such as dust, smoke particles or sea salt that are suspended in the atmosphere. Droplets may grow to visible size in a fraction of a second. However, the process then slows down. For further growth, collisions and fusing together of existing droplets must occur.

Supercooled water droplets

Supercooled water drops are common between 0°C and -20°C and may occur to -35°C in the atmosphere. Aircraft flying in cloud composed of supercooled water drops are susceptible to icing (Chapter 11).

Ice crystals

Ice crystals form and grow either by the direct change of water vapour to ice (deposition) or by the freezing of supercooled water droplets onto ice crystals.

Snowflakes

Snowflakes consist of aggregates of ice crystals. These may occur in a variety of shapes and forms depending on the temperature and the environment in which they form. The largest snowflakes occur when the temperature is slightly below freezing point and the atmosphere's moisture content is high.

8.6 Precipitation

Precipitation is defined as liquid or solid particles falling and reaching the ground. Snow, ice and water droplets that fall from a cloud but do not reach the ground are called virga. Precipitation can be associated with many aviation hazards, including very poor visibility, water ingestion, poor braking and flooding of runway surfaces. Unsealed airstrips may be unsuitable for air traffic for some days after heavy rain.

Drizzle

Drizzle consists of fairly uniform precipitation, composed exclusively of fine drops of water very close to one another. It is often observed to drift with the air.

Rain

Rain is composed of larger water droplets than drizzle. Drops tend to fall through the air straight to the ground. Clouds that are many kilometres in thickness produce large raindrops. Rain falls from clouds that are produced by widespread vertical motion, rather than convective motion. Because of the widespread nature of rain clouds, the precipitation tends to be continuous. On the other hand the intensity can vary over time.

Showers

Showers are a product of convective clouds. They are characterised by their abrupt start and finish and by the rapid and sometimes large variations in the intensity of the precipitation. Between showers, sunny breaks may appear unless stratiform clouds fill the intervals between the cumulus clouds. Showers may consist of water drops, hail or snow.

Snow

Snow is precipitation in the form of aggregated ice crystals called snowflakes. Most of these are branched and are sometimes star-shaped.

Hail
Hail consists of ice stones with diameters mostly ranging from a few millimetres to over two centimetres. Much larger hail can fall from severe thunderstorms. During the Sydney hail storm of 1999, hail stones measured up to 9 cm. Larger hail stones have been recorded. Hailstones may fall singly or frozen together in irregular masses and are composed of clear ice or alternate clear and opaque layers.

Ice Pellets
Transparent, roughly globular grains of ice about the size of raindrops. The interior may be liquid and their shell may burst on striking a hard surface. These are partially frozen raindrops.

Soft Hail, Graupel and Snow Pellets
These are white, opaque, round or conical pellets of diameter less than 6 mm. A central crystal is covered with frozen cloud droplets (rime). They may have low density, are easily compressed and may shatter on striking a hard surface.

8.7 CLOUD DISPERSAL

Cloud development will naturally begin to weaken once any of the processes leading to its formation cease to operate. Other factors leading to cloud dispersal are:

- warming due to subsidence;
- precipitation and mixing with drier surrounding air;
- insolation often leads to the dissipation of low-level clouds, including fog, low stratus, stratocumulus and small cumulus. If sufficient solar radiation penetrates past or through clouds to the ground both the surface temperature and the mixing condensation level will rise. As a consequence the base of the cloud will also rise, the thickness of the cloud decrease and eventually the cloud will disappear completely. This process is sometimes referred to as 'burning off'.

Fair weather cumulus formed over the land by convection due to insolation is a daytime phenomenon. It usually appears in the late part of the morning, reaches maximum development during the afternoon and clears rapidly when the ground cools towards evening.

8.8 VISUAL IDENTIFICATION OF CLOUDS

Although the classification of clouds into typical forms is of great use, the problem of identifying clouds is not always an easy one. It does not overcome the difficulties that arise from the gradual transition between the various types of clouds.

Reliable observations of cloud can best be made, by keeping a close and continuous watch on their development and by observing associated weather. It is not always sufficient merely to make a brief examination of the sky.

The definitions, two-letter abbreviations and associated weather conditions for the 10 cloud genera are as follows:

Cirrocumulus, Cc
Thin, white patch, sheet or layer of cloud without shading, composed of very small elements in the form of grains or ripples, joined together or separate and more or less regularly arranged. The elements have an apparent width of less than one degree (apparent width of little finger at arm length). Composed of ice crystals. Cirrocumulus clouds are not very common.

Cirrostratus, Cs
Transparent whitish veil of fibrous or smooth appearance, totally or partly covering the sky and generally producing halo phenomenon (a luminous white ring around the sun or moon usually with a faint red fringe on the inside). Composed of ice crystals. Aircraft condensation trails can spread out and form a thin layer of cirrostratus.

Cirrus, Ci
Detached clouds in the form of white delicate filaments of white or mostly white patches or narrow bands. These clouds have a fibrous or silky appearance. Composed of ice crystals.

Altostratus, As

Greyish or bluish cloud sheet of fibrous or uniform appearance totally or partly covering the sky and having parts thin enough to reveal the sun at least vaguely as would be seen through ground glass. Precipitation in the form of rain or snow can occur with this type of cloud.

Nimbostratus, Ns

Dark grey cloud layer generally covering the whole sky and thick enough throughout to hide the sun or moon. The base appears diffuse due to more or less continuously falling rain or snow. At times it may be confused with altostratus cloud, but its darker grey colour and lack of a distinct lower surface provides a distinction from altostratus cloud. Heavy continuous rain or snow usually accompanies nimbostratus cloud.

Altocumulus, Ac

A layer or patches of cloud composed of flattened globular masses, the smallest elements of the layer being the apparent width of two fingers at arms length. Altocumulus clouds are usually thin, and either white or grey in colour. The elements are arranged in groups in lines or in waves, which may be joined to form a continuous layer or appear in broken patches. Coronae (one or more coloured rings around the sun or moon) are a characteristic of this cloud, while irisation (coloured bands predominantly green and pink often with pastel shades) may appear along the thinner edges of the elements. In an unstable atmosphere the vertical development of altocumulus may be sufficient to produce precipitation in the form of light showers. Virga (precipitation not reaching the ground) is often a feature of altocumulus.

Cumulonimbus, Cb

Heavy, dense clouds with rounded towers, rising to considerable vertical extent. At least part of its upper portion is fibrous or striated, often appearing as an anvil or vast plume. The base of the cloud appears dark and stormy looking. Low ragged clouds are frequently observed below the base. Other varieties of low cloud, cumulus and stratocumulus can be in close proximity to cumulonimbus. Lightning, thunder, strong wind squalls and even tornados are characteristic of this type of cloud. Cumulonimbus can produce moderate to very heavy showers of rain, snow or hail. A green tinge to the cloud often indicates the presence of large hail.

Cumulus, Cu

Detached clouds, generally dense and with sharp outlines, developing vertically in the form of rising mounds, domes or towers, of which the upper part often resembles a cauliflower. The sunlit parts of these clouds are mostly brilliant white; their base is relatively dark and nearly horizontal. Precipitation in the form of showers of rain or snow may occur with large cumulus. Given the right conditions, cumulus clouds will grow into cumulonimbus clouds.

Stratocumulus, Sc

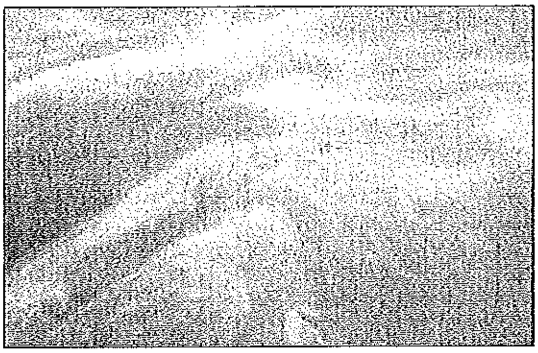
Grey or whitish patch or sheet of cloud that has dark parts composed of rounded masses or rolls that may be joined or show breaks between the thicker areas. Most of the rounded masses have an apparent width of more than 5 degrees (the apparent width of three fingers at arms length). The associated weather, if any, is very light rain, drizzle or snow. Stratocumulus is often observed to form from the spreading out of the tops of cumulus.

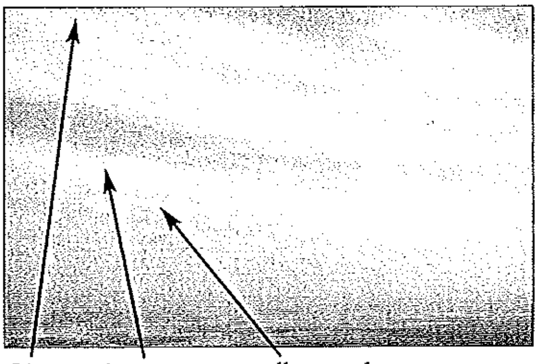
Stratus, St

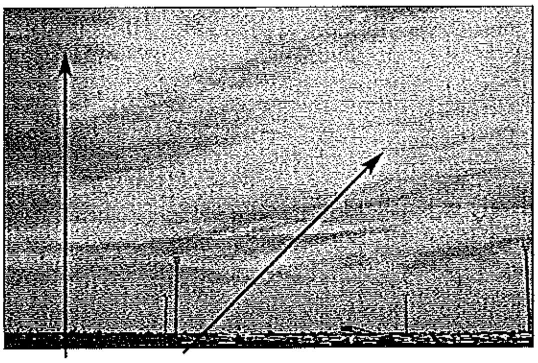
Generally, grey cloud layer with a uniform base. Precipitation in the form of drizzle may occur. Stratus may appear as shreds or fragments below the base of nimbostratus or altostratus. Stratus sometimes forms by the lifting of fog. Stratus cloud also occurs at frontal surfaces and in precipitation, although in these cases it tends to be patchy rather than a continuous deck.

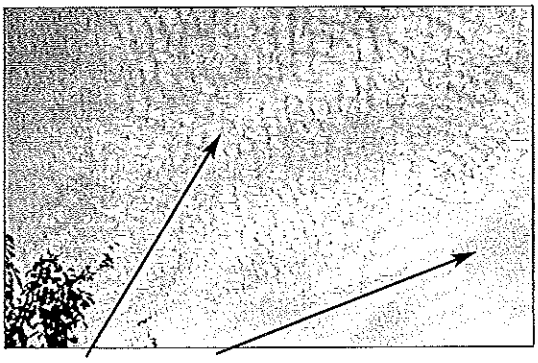
Figure 8.9 depicts many of the classical cloud forms and some variations.

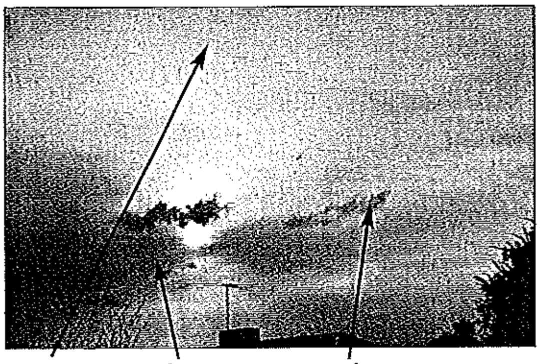
Figure 8.9
Cloud types

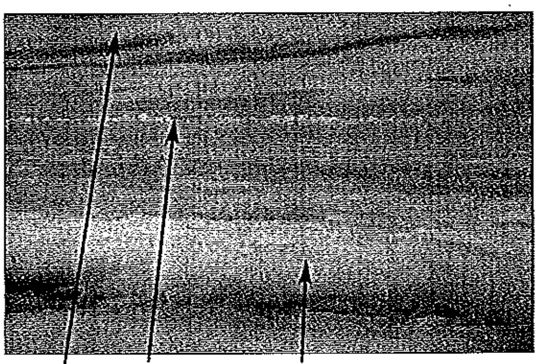

Cirrus
Photo© G. E. Trologgon


Cirrus, cirrostratus, small cumulus.
Photo© G. E. Trologgon


Cirrocumulus, cirrostratus.
Photo© G. E. Trologgon


Cirrocumulus, cirrostratus.
Photo© G. E. Trologgon


Cirrostratus, altostratus, ragged stratus.
Photo©G. E Trologgon


Cirrus, altocumulus and stratocumulus.
Photo©G. E Trologgon


Altostratus, altocumulus.
Photo©G. E Trologgon

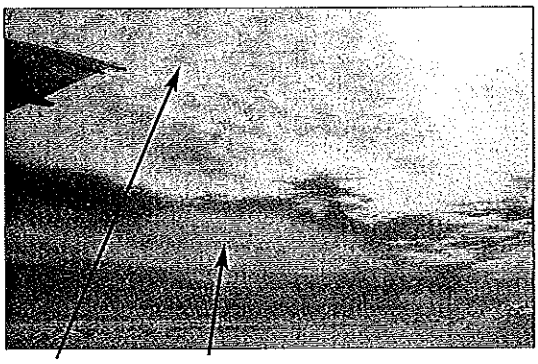
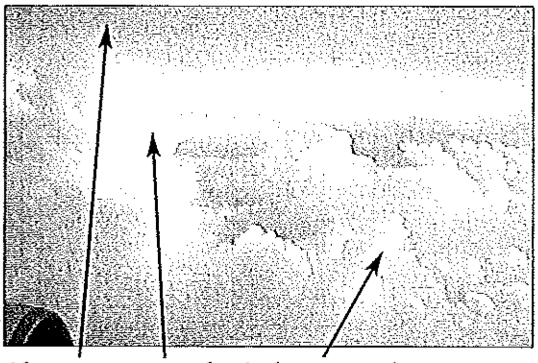
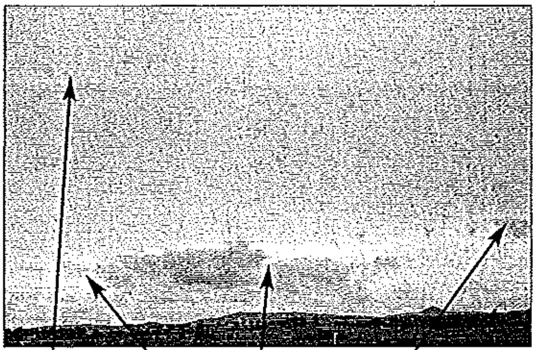

Altocumulus, cirrostratus.
Photo©G. E Trologgon

Figure 8.9
Cloud types

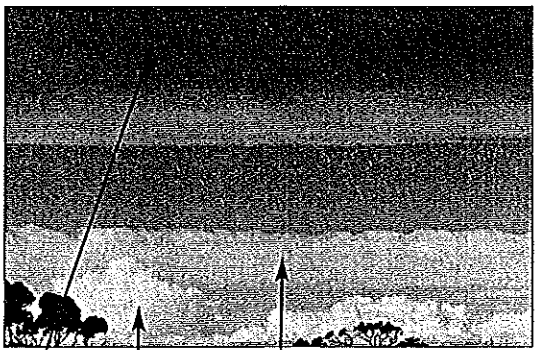


Altostratus, cumulonimbus, cumulus.
Photo©G. E Tratoggan



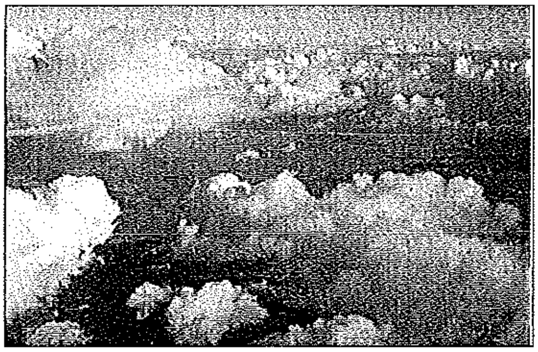
Altostratus, cumulus, stratocumulus, stratus.
Photo©G. E Tratoggan

Altocumulus.
Photo©G. E Tratoggan

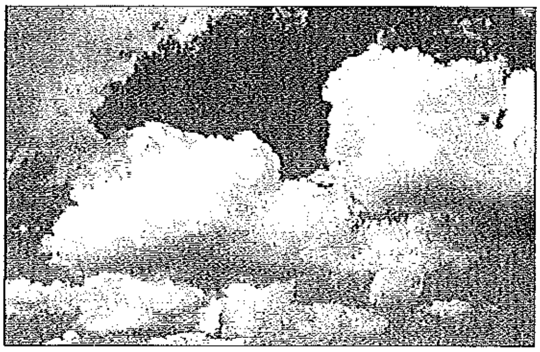


Altostratus, cumulus, stratocumulus.
Photo©G. E Tratoggan

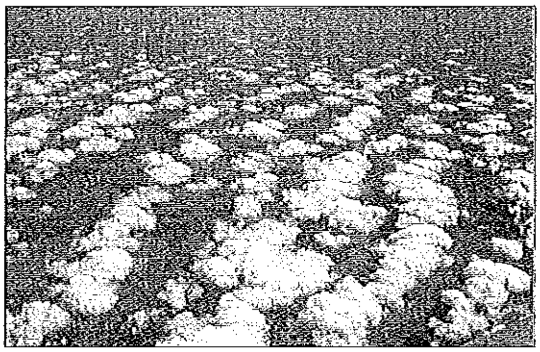
Cumulus.
Photo©G. E Tratoggan



Cumulus.
Photo©G. E Tratoggan

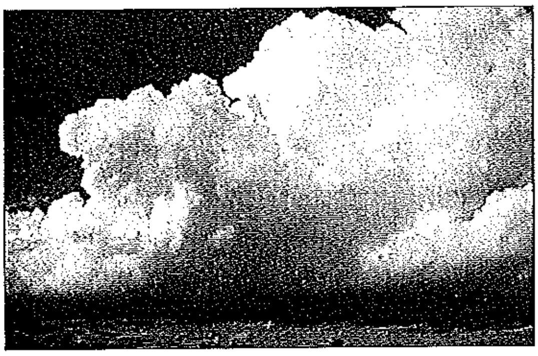


Cumulus.
Photo©G. E Tratoggan

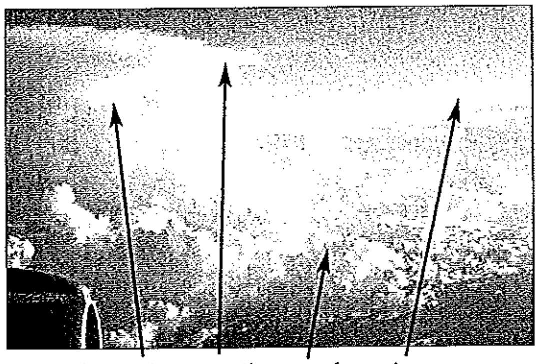


Cumulus.
Photo©G. E Tratoggan

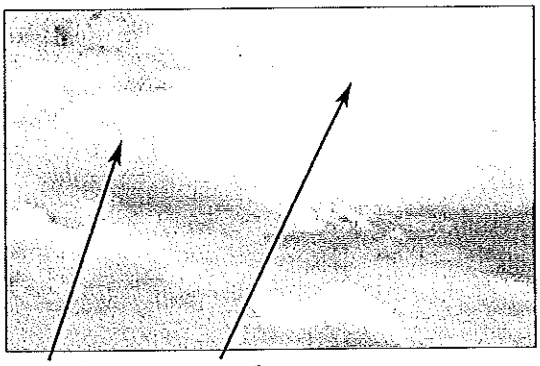
Figure 8.9
Cloud types



Cumulus.
Photo©G. E Tratoggan



Cumulonimbus, anvil, cumulus, cirrus.
Photo©G. E Tratoggan



Cumulus, stratocumulus.
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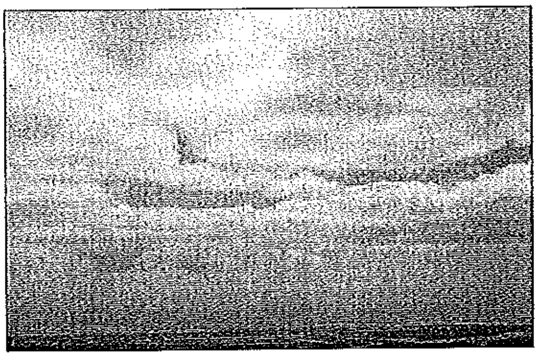

Stratocumulus.
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Cumulus tending to be stratocumulus.
Photo©G. E Tratoggan

Stratocumulus.
Photo©G. E Tratoggan

Stratocumulus.
Photo©G. E Tratoggan

Stratocumulus.
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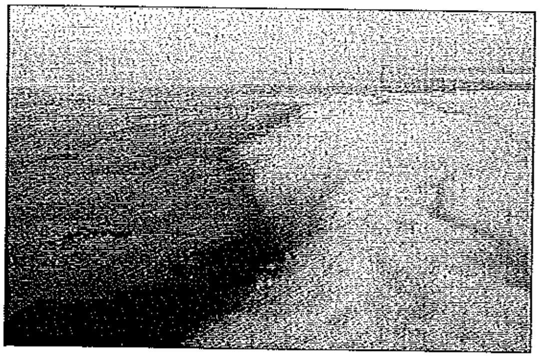
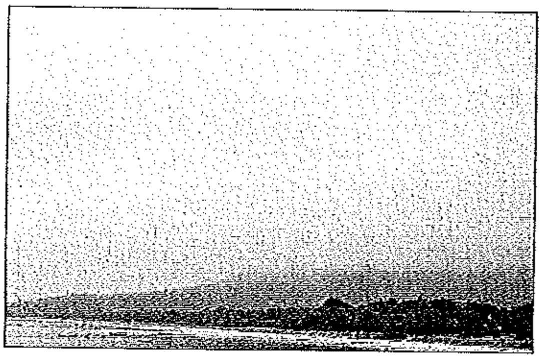
Figure 8.9
Cloud types

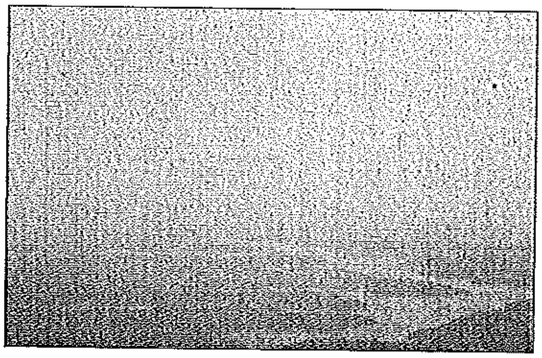


Stratus close to the ground, possible fog below.
Photo©G. E Trafoggon

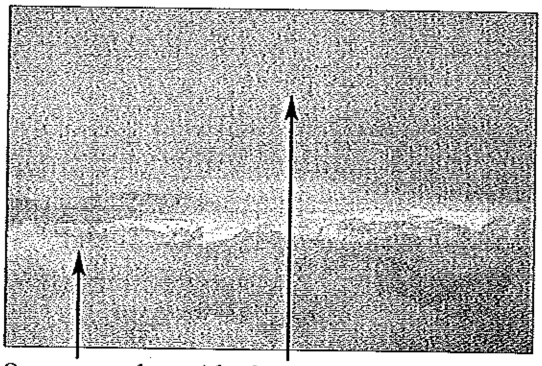


Stratus obscuring hills.
Photo©G. E Trafoggon

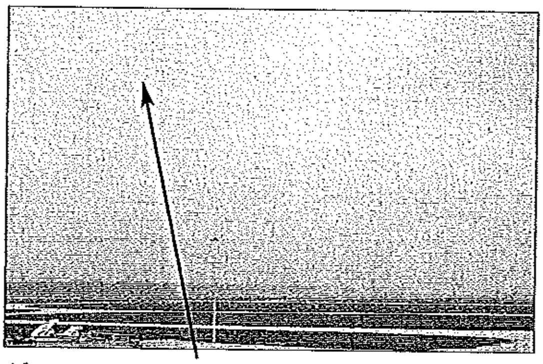
Fog obscuring the ground.
Photo©G. E Trafoggon



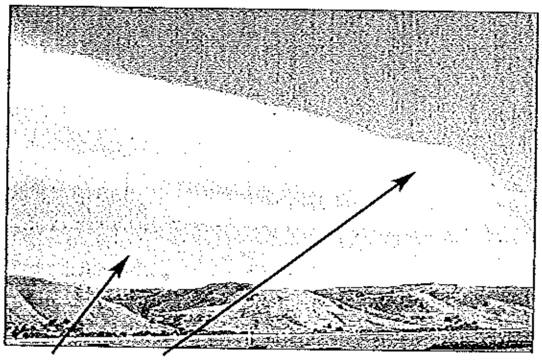
Altostratus or nimbostratus with rain reducing visibility.
Photo©G. E Trafoggon



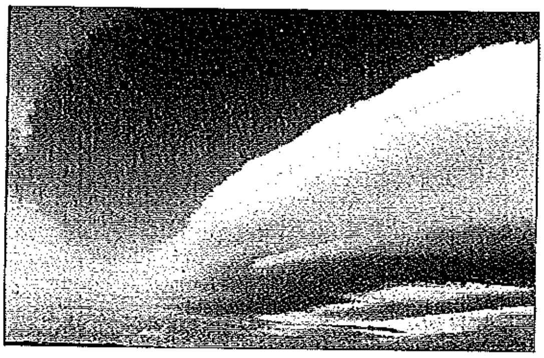
Stratocumulus with altostratus above.
Photo©G. E Trafoggon



Altostratus or nimbostratus with rain is reducing visibility.
Photo©G. E Trafoggon

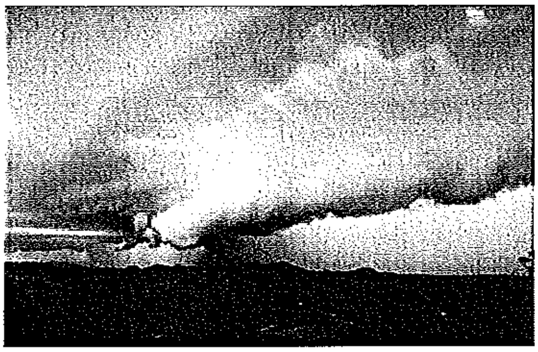


Cumulus, lenticular.
Photo©G. E Trafoggon

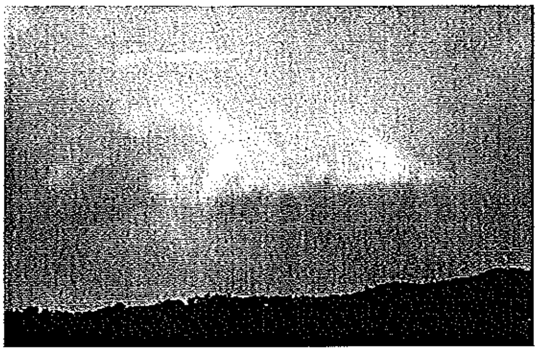


Lenticular.
Photo©Gordon Richardson

Figure 8.9
Cloud types

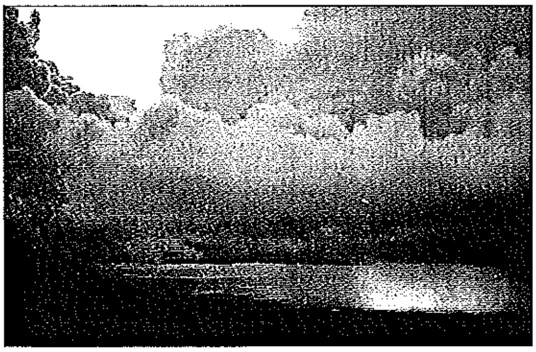

Wall cloud beneath cumulonimbus.
Photo©Gordon Garradd

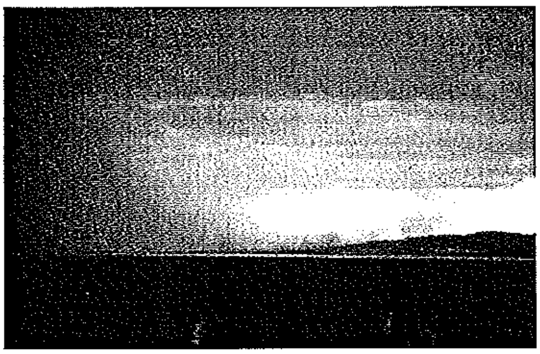

Wall cloud beneath cumulonimbus.
Photo©Gordon Garradd

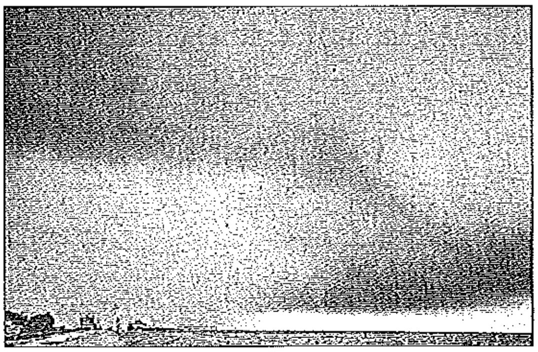

Hail falling from cumulonimbus.
Photo©Gordon Garradd

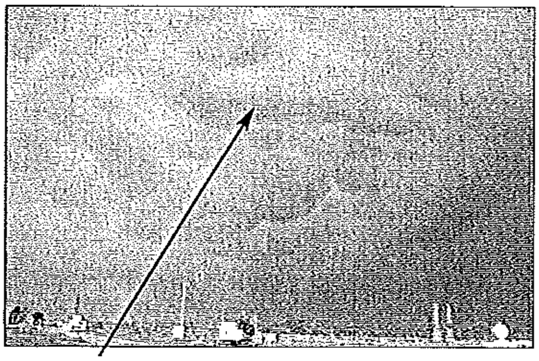

Cumulus, cumulonimbus, anvil.
Photo©Gordon Garradd


Cirrus anvil projecting from cumulonimbus.
Photo©G. E Tralaggan

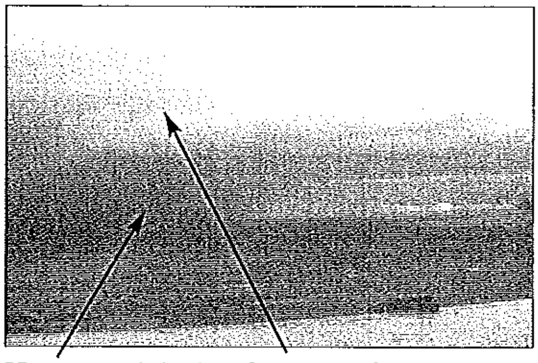

Showers below a line of large cumulus.
Photo©G. E Tralaggan


Hook signature of a microburst.
Photo©Gordon Garradd


Wall cloud beneath a cumulonimbus, heavy rain.
Photo©G. E Tralaggan



Mammatus beneath cumulonimbus.
Photo©G. E Trofoggon



Heavy precipitation from cumulus.
Photo©G. E Trofoggon

Fog

Fog is whitish cloud in contact with the ground; reducing visibility to below 1000 metres. It is discussed in Chapter 13.

The following ATSB report clearly indicates that VFR flight into cloud is potentially dangerous and can be fatal.

> Witness reports indicate that the pilot had established the aircraft below the cloud layer some distance from Jerilderie. The most likely reason for this was in order to make a visual approach to Jerilderie. However, in the area of the cold front, instrument meteorological conditions extended from the base of the cloud layer to the ground. With visibility rapidly reducing, the pilot had the option of continuing straight ahead and climbing in instrument meteorological conditions to the lower safe altitude of 3300 feet, or turning back to remain in visual conditions. The pilot initiated a left turn and entered instrument meteorological conditions close to the ground. The turn would have required the pilot to fly with sole reference to flight instruments. The transition from visual flight to flight by sole reference to instruments may take several seconds, and an aircraft in a turn will generally loose altitude until the pilot takes corrective action. However, as the aircraft was at low altitude when it began the turn, it probably struck the ground before the pilot had completed his transition to instrument flight.
>
> Although the pilot held an instrument rating, he had minimal experience of flight in actual instrument meteorological conditions. He may not have previously experienced the conditions that confronted him on this occasion. The combination of rapidly deteriorating weather, gusting winds and low altitude in conjunction with low experience and recency with actual flight in instrument meteorological conditions would have required a high level of skill and experience.

8.9 FLYING CONDITIONS IN CLOUD

Flying conditions in cloud vary greatly. A summary of cloud type and associated flying conditions appears in Table 8.2.

Table 8.2 Flying conditions associated with clouds.

			Associated Flying Conditions		
Cloud Type	**Brief Descrip. of Cloud**	**Associated Weather**	**Turbulence**	**Icing**	**General**
Cirrus (Ci)	High level cloud. White. Fibrous or threadlike appearance.	Nil	Little unless associated with a jet stream.	Nil	Indicates the possibility of formation of persistent contrails.
Anvil cirrus (Ci)	Thick fibrous anvil shaped cirrus.	Top part of cumulonimbus.	Turbulence association with Cb. Can be severe even above cloud.	Usually too high for significant icing.	If flying 'over the top' of cumulus sky gives warning of Cb below.
Cirrostratus (Cs)	High level cloud. White. Sheet or layer. Halo phenomena.	Nil. If increasing and thickening may indicate deterioration of weather.	May be felt on entering cloud – usually only light.	Usually too high for significant icing.	Indication of formation of persistent contrails.
Cirrocumulus (Cc)	High level cloud. White.	Nil	Globular form of cloud indicates presence of turbulence.	Too high for significant icing. Cloud usually dissipates rapidly.	Indicates formation of contrails.
Thin altostratus (As)	Middle level cloud. Bluish sheet or layer. Sun appears as through ground glass.	Generally nil. Light rain, usually not reaching the ground, may be encountered	Little in cloud. Distinct bumps felt on entering or leaving cloud.	Some risk. Usually light rime as cloud particles small and temp. usually low.	May thicken and lower into thick As or Ns.
Thick altostratus (As)	Bluish grey sheet or layer. Sun appears as through ground glass through thinner portions.	Light to moderate rain or snow.	Generally light in cloud; may be moderate to severe at fronts, over highlands. Bumps on entering or leaving.	Definite risk. Moderate rime. Clear ice possible in lower levels of cloud.	May lower and thicken into Ns Beware of embedded Cb.
Altocumulus (Ac)	Middle level cloud. White to grey.	Nil	Usually light.	May be light rime.	Nil
Altocumulus lenticularis	Lens or almond shaped. Forms in crests of mountain waves.	Nil	Form of cloud indicates wave form in atmosphere with consequent turbulence, usually not severe.	May be light rime.	Nil
Altocumulus castellanus	Turret or castle shaped protruberances on common base.	Possible rain showers.	Moderate to severe.	May be light rime.	Indicates instability in upper layers.

Cloud Type	Brief Descrip. of Cloud	Associated Weather	Turbulence	Icing	General
			Associated Flying Conditions		
Nimbostratus (Ns)	Low or middle level cloud. Grey. Sheet or layer. Sun obscured.	Heavy continuous rain or snow.	Generally light in cloud; may be moderate to severe at fronts, over highlands. Bumps on entering or leaving.	Definite risk. Moderate rime. Clear ice probable in lower levels of cloud, particularly when turbulence present. Accumulation of ice may be great due to extensive cloud coverage.	Cu or Cb may be embedded in a large expanse of Ns in some situations.
Cumulus (fine weather) (Cu)	Low level cloud. Cellular. Flat base. Small vertical extent. Cauliflower shaped.	Nil	Light to moderate.	Little risk. Freezing level usually above cloud.	Usually isolated or well scattered: dissipate at night.
Large cumulus (Cu)	Low level cloud. Cellular. Flat base. Large vertical extent. Cauliflower like bubbling.	Showers of rain or snow.	Moderate to severe both in and below cloud. Violent on entering or leaving.	Definite icing risk. Clear ice just above freezing height.	Can be as dangerous as Cb.
Cumulonimbus With or Without an anvil (Cb)	Low level cloud. Cellular. Very large vertical extent. Tops fibrous or striated: may be in shape of anvil.	Thunderstorms, lightning, showers of rain, snow or hail.	Severe both in and below cloud. Very violent on entering or leaving.	Definite risk, Dangerous clear ice likely.	Most dangerous.
Stratocumulus (Sc)	Low level cloud. Mostly grey.	May be drizzle.	Light to moderate beneath and in cloud – bumpiness passing through inversion at cloud top, smooth above	Occasional rime if freezing height low enough.	Change in air density through the inversion causes change in aircraft performance.
Stratus (St)	Low level cloud. Greyish, generally thin sheet or layer. Sun, if visible, clearly discernible. May be ragged.	May be drizzle.	Light. May be inversion as with Sc.	Usually nil.	Change in air density through inversion causes change in aircraft performance. At take off important to attain ample flying speed early in climb; care in descent.
FOG	Cloud on the ground.	Visibility below 1000 metres. Obliterates view of ground.	Nil	Nil	Very poor visibility

WIND

Wind flows over the earth's surface in much the same way as water flows in a stream. The natural tendency is for smooth flow but when restrictions and obstructions are encountered the flow may become chaotic with reverse flows, swirls, vortices, waves and wind shear that can quickly overcome a pilot's ability to control an aircraft.

9.1 Measurement Of Wind

It is sometimes difficult to obtain truly representative values of surface wind speed and direction because the motion of the air is affected by such factors as the roughness of the ground, the type of surface, the presence of buildings and other obstructions to air flow as well as the stability of the atmosphere.

In addition, wind speed normally increases with height. It is therefore necessary to specify a standard height for making surface wind measurements, so that winds at different locations can be compared.

The standard exposure for surface wind instruments is over level open terrain 30 feet above the ground. Open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten times the height of the obstruction.

Aerodrome meteorological observations (METAR/SPECI) report wind speed and direction averaged over the 10 minutes up to the time of the report. Wind direction relates to true north and is the direction from which the wind is blowing. Speed is reported in knots. A reported wind of 31510KT indicates that the wind is blowing from the northwest at a speed of 10 knots.

NOTE: The Bureau of Meteorology's Automatic Weather Information Broadcast (AWIB) reports one minute updates (of the two minute mean) with wind direction relative to magnetic north.

9.2 Pressure And Wind

The relationship between pressure and wind is one of the fundamentals of meteorology.

Buys Ballot's law describes one aspect of the relationship for large-scale flow:

If an observer stands with his back to the wind the lower pressure is on his right in the southern hemisphere, on his left in the northern hemisphere.

An observer in the southern hemisphere standing with his back to the wind (imagine standing at any point A in Figure 9.1) the low-pressure region will be on the right and the high-pressure region will be to the left.

For large-scale flow as depicted in Figure 9.1, Buys Ballot's is a useful law, but it often does not apply to small-scale flow. For example the rule may not apply to winds that are deflected by terrain or locally generated winds such as sea-breezes and katabatic winds.

Air moves in response to pressure-gradient forces that build up between areas of high and low pressure. The greater the pressure difference, the greater is the pressure-gradient force and hence the faster the air tends to flow.

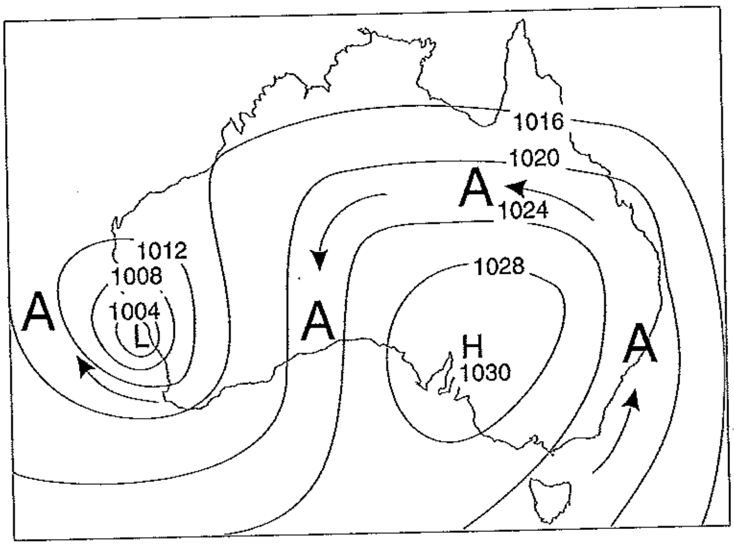


Figure 9.1
Points A are reference points to apply Buys Ballot's law, i.e. with wind to your back high pressure is to the left and low pressure to the right.

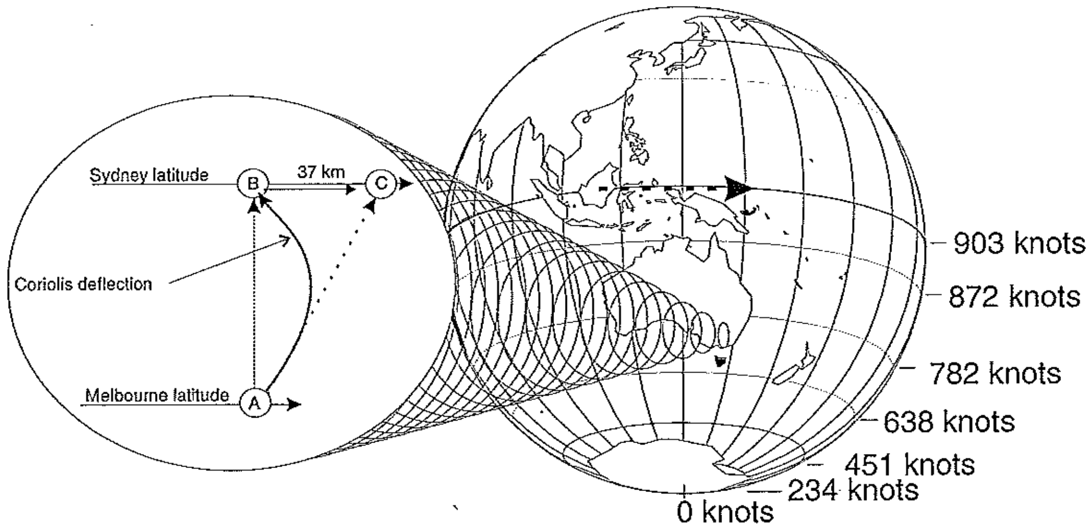


Figure 9.2
The diagram shows the variation in earth speed and the Coriolis deflection between Melbourne and Sydney latitudes. For a person standing at point A who wants to fire a missile to hit point B (directly north) the missile would have to be aimed toward point C, (to the right of the target). This is because the earth is rotating much faster north of the starting point. So by the time the missile has traveled northward to the Sydney latitude, the original target has shifted 37 kilometres to the right.

It might be thought that the wind should flow directly across isobars from high to low pressure. However, the observed behaviour is that the wind two to three thousand feet above the surface, usually flows parallel to the isobars, while the surface wind blows slightly across the isobars, so there must be some other factors to consider.

There are two other forces acting on the airflow. The first, the Coriolis force, is due to the earth's rotation. The second, the frictional force, is due to the frictional drag of the earth's surface.

9.3 Coriolis Force

The earth's rotation creates an apparent force that deflects the wind from a straight path across the earth's surface. This force is called the Coriolis force.

The Coriolis force acts on any object moving across the face of the earth (including rivers), due to the varying eastward speed of the earth's surface from pole to the equator as indicated in Figure 9.2. Consider Figure 9.2: Sydney (latitude 34 degrees south) travels at 750 knots eastward. Melbourne (latitude 38 degrees south) travels at only 710 knots eastward. If a projectile is fired, due north, from 38 degrees south, it has an easterly speed through space of 710 knots. But the point due north has an easterly speed 40 knots greater. If it takes the projectile half an hour to reach 34 degrees south, it will be 37 km west of the target – an apparent deflection (from the dotted line) to the left of the intended path.

Coriolis force has the following properties:

- it acts perpendicular to the motion, deflecting motion to the left in the southern hemisphere (to the right in the northern hemisphere);
- it is directly proportional to the wind speed: zero when the air is stationary and at a maximum when the wind speed is at a maximum;
- the magnitude depends on latitude: it is zero at the equator and large near the poles. To make sense of this consider the difference in speed between 15 and 30 degrees south (872 - 782 = 90 knots) and the difference between 15 degrees north of the pole and the pole (234 - 0 = 234 knots). The deflection then is obviously greater near the pole.

Although the Coriolis force affects all air motion, on all scales, its effect is minimal for very small-scale air movement and very important for large-scale circulations. Deflections are not perceivable over very short distances but they are important over longer distances. Pilots must make navigational corrections to allow for the Coriolis effect.

9.4 Frictional Force

Frictional forces retard wind flow near the earth's surface. The depth of the atmosphere through which frictional forces act varies with the degree of stability and the roughness of the surface, but is generally accepted to be 2000 to 3000 feet. The frictionally affected layer is called the friction layer or the boundary layer.

The result of frictional retardation is that the Coriolis force is reduced and no longer counters the pressure gradient force. The wind therefore flows slightly across the isobars in the direction of the pressure gradient force; that is, towards lower pressure.

The reduction in wind speed in the friction layer and the extent of cross-isobar flow, caused by the Coriolis force, depends on the roughness of the underlying surface. Over the sea, where the friction is less than over the land, the surface wind speed is reduced to about two-thirds of the wind above the friction layer, and the flow is at an angle of about 10 degrees to the isobars. Over the land, the surface wind may be only half or even one-third of the wind above the friction layer and the cross-isobar angle of the flow will be 25 to 30 degrees before allowing for topographical or diurnal effects. See Figures 9.3 and 9.4 for example of the balance of forces in the southern hemisphere when friction is included.

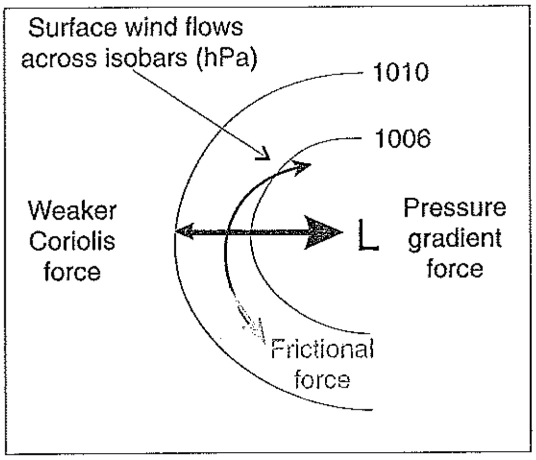


Figure 9.3 Surface wind flowing across isobars towards low pressure (southern hemisphere case).

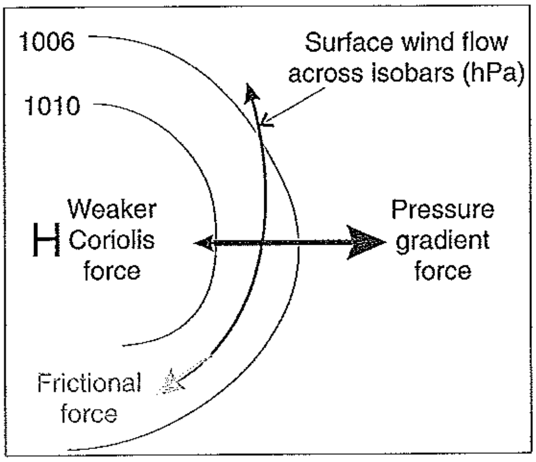


Figure 9.4 Surface wind flowing across isobars away from high pressure (southern hemisphere case).

9.5 Wind Flow Above The Friction Layer

Free of the friction-layer, winds blow parallel to isobars either as straight, cyclonic or anticyclonic flow.

Straight-line flow

When the pressure gradient and Coriolis force are in balance, straight-line flow occurs, i.e. wind doesn't flow toward low or high pressure (Figure 9.5).

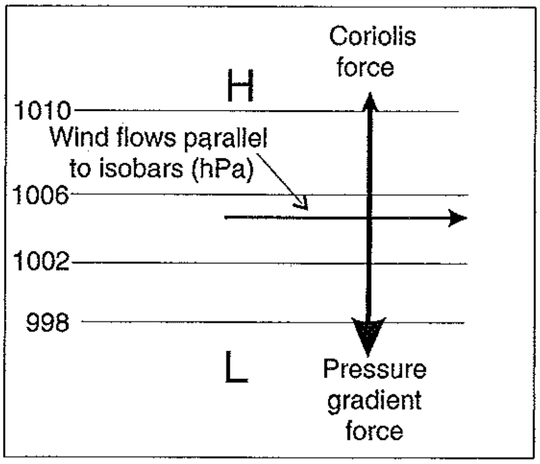


Figure 9.5 Straight line flow (southern hemisphere).

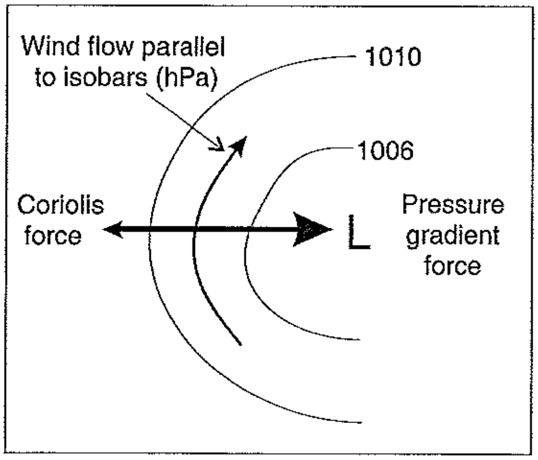


Figure 9.6 Wind flowing parallel to isobars around low pressure, in a clockwise direction, above the friction layer, in the southern hemisphere.

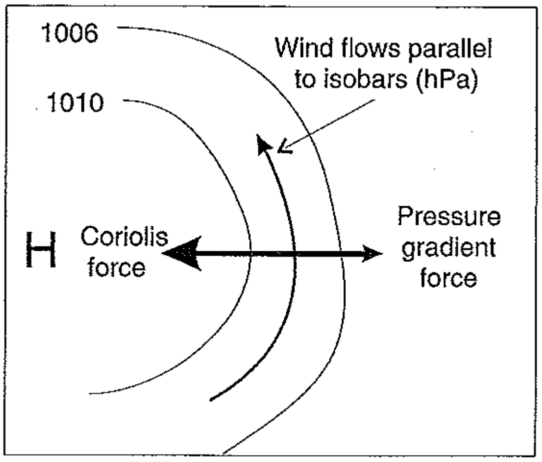


Figure 9.7 Anti-cyclonic flow above the friction layer in the southern hemisphere.

If the isobars are curved as is the case around pressure systems, generally the pressure gradient force is greater than the Coriolis force around lows and the Coriolis force is greater then the pressure gradient force around highs leading to cyclonic and anticyclonic flow.

Curved, cyclonic flow

When the pressure gradient force is greater than the Coriolis force, the flow follows a curved path around low pressure (Figure 9.6).

Curved, anticyclonic flow

When Coriolis is the larger force, curved flow is around high pressure (Figure 9.7).

These relationships break down in the equatorial region when Coriolis force becomes so small that its influence is negligible. At the equator Coriolis force is zero, and is negligible from there to about 15 degrees latitude.

Because the relationship between wind speed and pressure gradient breaks down in equatorial regions isobaric charts are not used there to represent weather patterns. Instead streamline charts that show wind direction are used rather than the pressure pattern.

9.6 Convergence and Divergence

If there is a net gain or loss of air above an area in a column from the earth's surface to the top of the atmosphere, the surface pressure will change. A loss of air leads to a fall in pressure and a net gain of air is associated with a pressure rise. Falls and rises in surface pressure often result from surface convergence and divergence respectively:

- convergence occurs when there is a net horizontal inflow of air into a surface region (termed horizontal convergence). The accumulated mass of air near the surface leads to up motion;
- divergence occurs when there is a net horizontal outflow of air at the surface (termed horizontal divergence). The deficit of air at low levels leads to downward motion.

Developing surface depressions and troughs of low pressure are associated with convergence in the lower troposphere and divergence aloft. The divergence aloft must be greater than that of convergence near the earth's surface for the surface pressure to fall. Figure 9.8 shows how horizontal divergence at X is associated with horizontal convergence at A. This is linked with upward motion.

By contrast, developing anticyclones and ridges of high pressure are associated with convergence aloft and divergence in the lower troposphere. These effects are linked with downward motion of the air. Figure 9.8 shows the horizontal convergence at Y is greater than the horizontal divergence at B, when surface pressure is increasing.

If a rapid fall of pressure occurs at A, a low-pressure area develops and boundary layer air is accelerated towards that region by the action of the pressure gradient force. Slow upward motion (ascent) may then take place over a wide area. Thick masses of cloud and precipitation may occur if the moisture content of the air is high enough.

A rapid rise of pressure near B leads to the development of a high-pressure area in that region. Slow downward motion (subsidence) over a wide area inhibits cloud development.

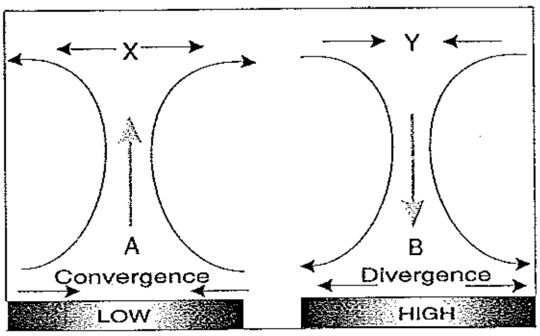


Figure 9.8
Convergence and divergence associated with up and down motion in the atmosphere. Up motion is occurring at A above the convergent low-pressure region, while rising air diverges at X. Down motion occurs over a high pressure divergent region at B while in the upper air convergence occurs at Y.

9.7 Backing and Veering

Backing and veering are the two terms used to describe changes in wind direction. If the wind direction changes in an anticlockwise direction it is said to back. If it changes in a clockwise direction it is said to veer. In Figure 9.9, if the wind changes from a NW to SW direction the wind has backed. Veering would occur if the wind changed from the SW to the NW.

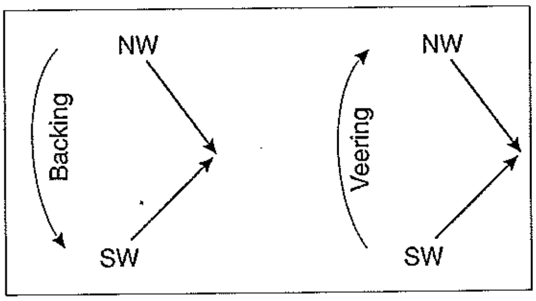


Figure 9.9
Backing and veering of wind direction.

9.8 Gusts and Squalls

Gusts are increases in wind speed lasting for just a few seconds and are indicative of instability and turbulence in the boundary layer. In the absence of any showers, thunderstorms or frontal systems the strength of wind gusts is typically 30–40% greater than the mean wind but can be up to 100%, with the latter more likely at lower mean wind speeds. However, wind gusts can be much higher in the vicinity of showers thunderstorms and frontal systems. These phenomena frequently superimpose locally generated winds over the mean winds. Pilots

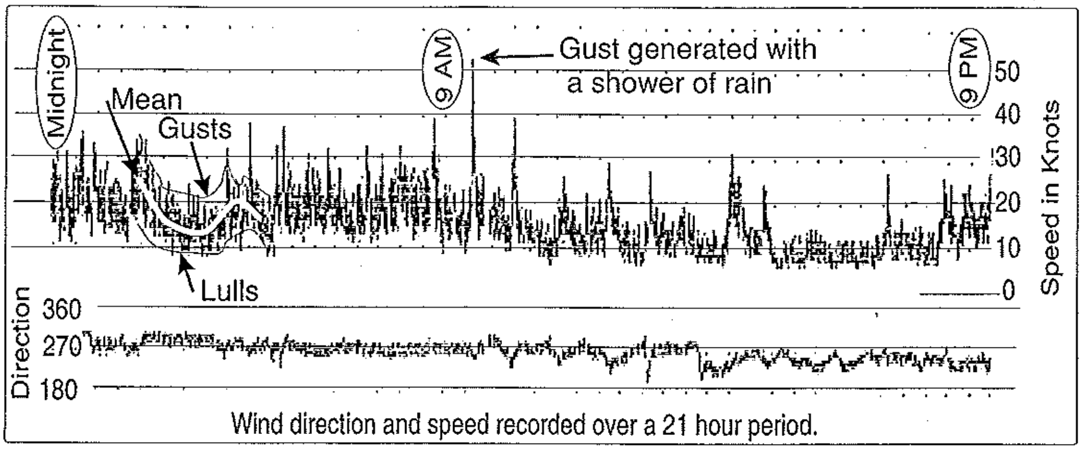


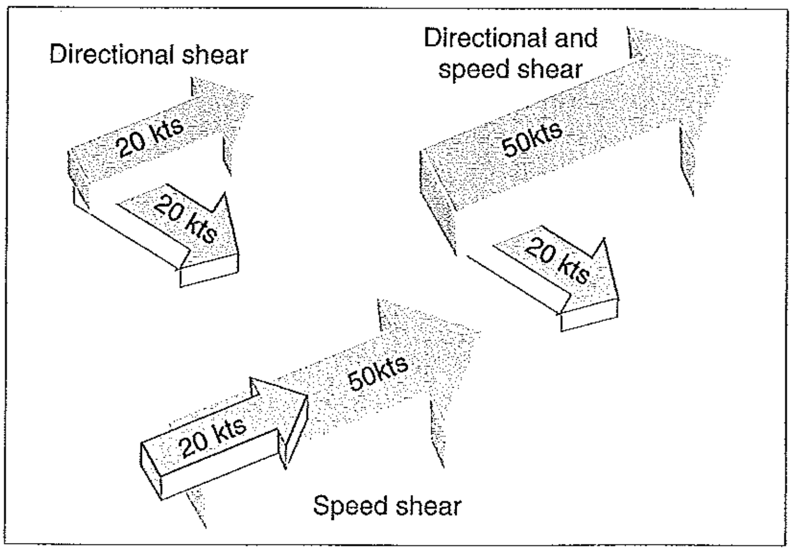
Figure 9.10
Recording of wind speed and direction illustrating the general variability of wind direction and speed over time and superimposed gusts.

should be aware that wind gusts significantly stronger than the mean wind are possible particularly during thê take off and landing stages of a flight in the vicinity of showers and thunderstorms. For surface winds in excess of 30 knots, pilots should also expect moderate or stronger turbulence, particularly if there is rough terrain nearby.

The wind recording in Figure 9.10 depicts the variability of wind speed and direction over a 21-hour period. The peak gusts have occurred with the passage of showers.

Squalls are strong winds that rise suddenly, last for some minutes, and then rapidly die away again. Technically, the term squall applies to an increase of at least 16 knots over the mean wind speed, the wind speed during the time of the squall must be 22 knots or more, and the duration must be at least one minute.

Figure 9.11
Wind shear induced by vertical acceleration in the same direction or by a marked change in wind direction or both.



9.9 Wind Shear

Wind shear is manifested by a marked change in wind direction and/or speed as depicted in Figure 9.11.

Wind shear is often signatured by clouds moving in different directions at different levels and by smoke plumes rising vertically before streaming off at acute angles. Waterspouts and tornados are manifestations of wind shear as are dust devils and gust fronts.

On a small-scale low-level wind shear is manifested as eddies and gustiness in the general wind flow. On the larger scale wind shear occurs when two air masses moving at different speeds and/or from different directions come into contact, one sliding over the other.

Thunderstorm outflows, land/sea-breezes, low-level jets, frontal systems, mountain waves and inversions are frequently associated with wind shear capable of upsetting the flight of an aircraft.

An extreme example of low-level wind shear was experienced on approach to Hobart Airport on 21 January 1997, when a shallow southeasterly wind change moved in beneath strong northwesterly winds. The plane experienced a wind change from 31531KT to 17911KT in the four seconds it took to descend from 736 feet to 704 feet. The wind shear was accompanied by severe turbulence that caused great consternation to crew and passengers.

Wind shear in the form of microbursts, in the vicinity of thunderstorms, has proved to be particularly hazardous to aircarft in the circuit areas of aeordromes. The phenomenon is discussed in detail in Chapter 12.

Significant wind shear is often encountered in the vicinity of and with frontal systems, low-level jets, strong and gusty surface winds, temperature inversions, mountain waves, sea-breezes and near obstacles that deflect and block wind flow.

Although wind shear may be present at all levels in the atmosphere, its occurrence in the lowest 2000 feet is of particular importance to aircraft landing and taking off. It can significantly impair aircraft performance and is particularly hazardous to aircraft approaching stalling speeds, especially in large jets where the lag between applying and achieving thrust is most noticeable.

Wind shear is often evident at low levels when upper level winds are decoupled from low-level winds. Low-level inversions can cut off, almost completely, the downward transfer of the horizontal wind energy or momentum to the boundary layer. Thus differences between surface flow and that above an inversion can be large. An aircraft descending through an inversion as illustrated in Figure 9.12 would pass through a zone of turbulence before experiencing a dramatic loss of lift and airspeed. In such a strong wind shear situation, significant turbulence would be generated across the top of the inversion.

Steeply banked turns, particularly for slow aircraft, may be hazardous in a low-level shear situation. If the aircraft is already close to stall, dipping one wing into air even a few knots slower could be potentially disastrous as indicated from an ATSB report of a fatal accident.

> The weather report indicated that wind conditions at the time were fresh and gusty from the east with a significant wind shear in the lower levels. The wind speed at 2000 feet above sea level was 22 knots, and at 3000 feet was 46 knots. The surface wind at the time of the accident was reported to be about 15 knots, but had become blustery and gusting to about 35 knots within about an hour of the accident. Consequently, it is likely that the wind strength and direction were variable and unpredictable at the heights at which the pilot was operating.
>
> In the absence of any associated aircraft mechanical fault, the evidence was consistent with the pilot losing control of the aircraft while maneuvering at low level in adverse wind conditions. The pilot's eagerness and lack of experience may have influenced him to operate the aircraft in a manner inappropriate for the weather conditions at the time.

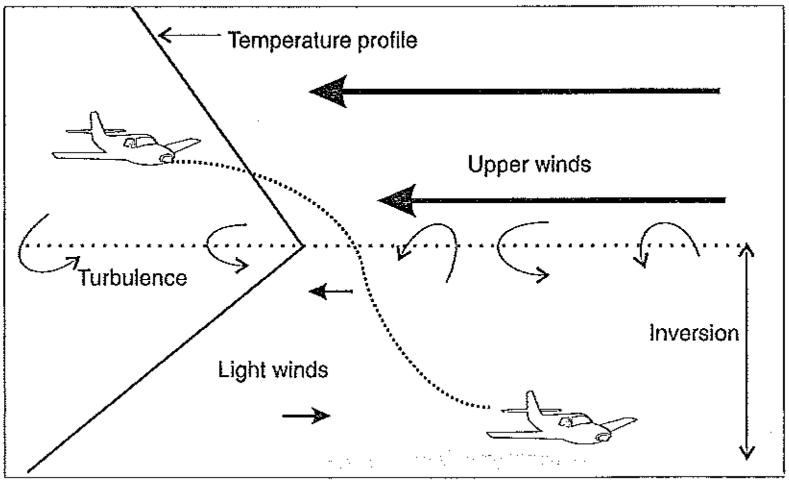


Figure 9.12
An aircraft initially flying into strong winds, experiences some turbulence and loses lift as it descends into an inversion layer where winds are light.

9.10 Sea-Breezes

The basic cause of a sea-breeze is the differential heating rates of land and sea under conditions of strong incoming solar radiation. During a sunny day the land heats more rapidly than the sea for two main reasons:

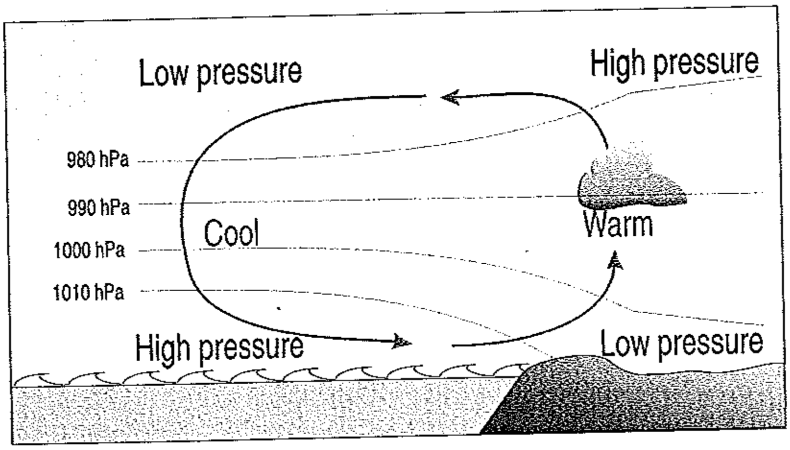


Figure 9.13
The structure of a sea-breeze circulation.

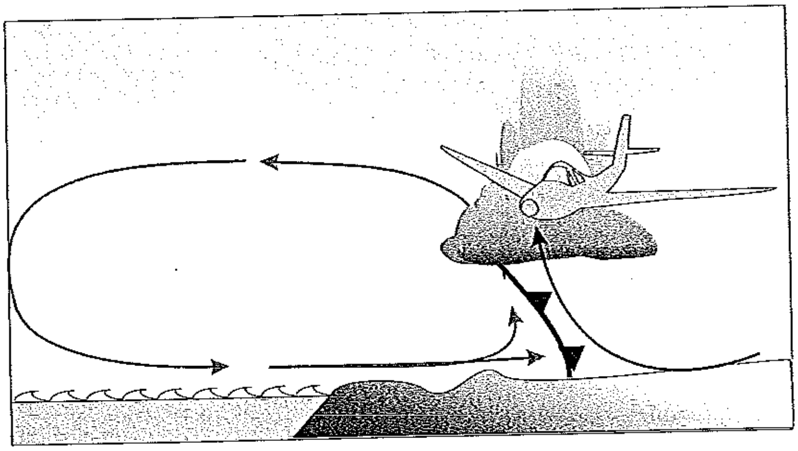


Figure 9.14
A well-developed sea-breeze frontal zone depicting cumulus clouds forming in the rising air and a glider taking advantage of the lift.

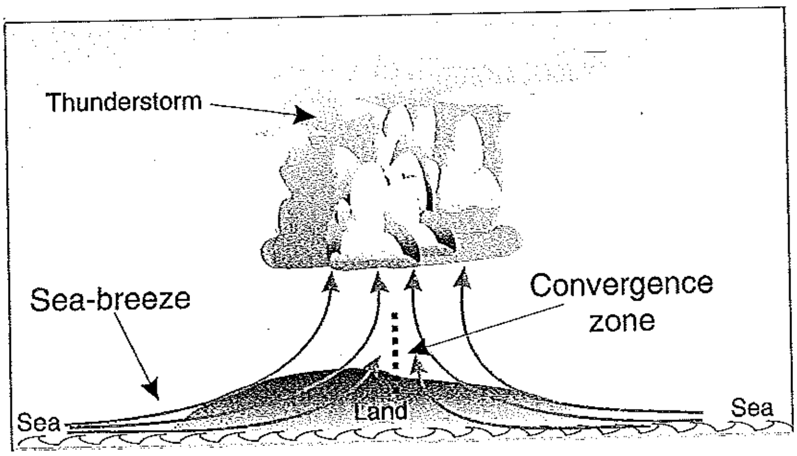


Figure 9.15
Sea-breeze convergence over an island or peninsula leading to development of a thunderstorm.

- land has a lower 'specific heat' than water. This means it requires less heat to raise the temperature;
- incoming heat affects only a shallow layer of earth because earth is a poor conductor whereas in water heat is spread through a significant depth by absorption, conduction and turbulent mixing.

The affect of differential heating over land and sea is shown in Figure 9.13. The warm air above the land expands and rises, thus the pressure aloft becomes greater than the pressure at the same height over the sea. As a result, the air aloft tends to move towards the top of the cooler column over the sea.

At sea level, the pressure over the sea is higher than that over the land because the air is denser and thus tends to move from the sea to the land, i.e. a sea-breeze develops. The circulation is completed as the cold air above the sea descends to replace the air moving towards the land.

At latitudes greater than about 20 degrees, the Coriolis force becomes strong enough to change the direction of the sea-breeze circulation, i.e. a sea-breeze that starts off as an easterly will, over time, turn northeasterly. The same is true for a sea-breeze starting off as a westerly. It will, over time, turn southwesterly. The turning typically occurs over a period of a few hours.

The greater the temperature contrast between land and sea, the greater is the potential for strong sea-breezes to travel well inland. However, the sea-breeze infiltration will be slowed and hindered by any opposing general wind. Glider pilots sometimes use the inland penetrating sea-breeze front to retain lift over distances of hundreds of kilometres (Figure 9.14). In Australia sea-breezes have been reported as far inland as 400 km, reaching places such as Canberra, Kalgoorlie and Renmark.

The sea-breeze front may penetrate inland and lift moist and unstable air sufficiently to trigger thunderstorms.

Sea-breezes from adjacent coastlines may converge over land as illustrated in Figure 9.15. The convergence accentuates vertical motion, which in turn can trigger showers

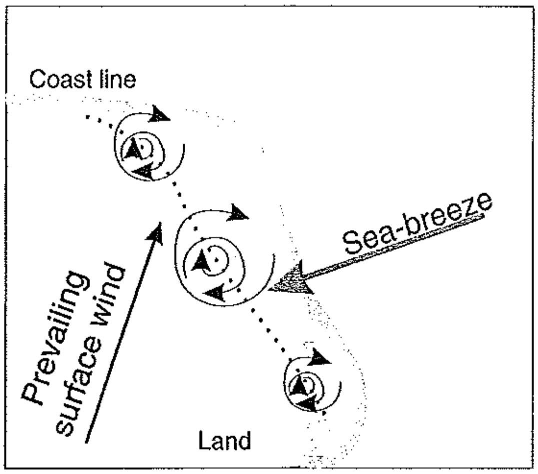


Figure 9.16
The interaction between prevailing winds and the sea-breeze can generate circulations sometimes seen as dust devils.

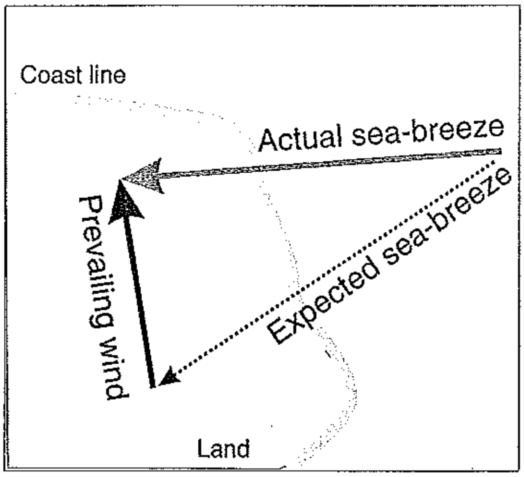


Figure 9.17
The expected sea-breeze direction is modified by the prevailing wind.

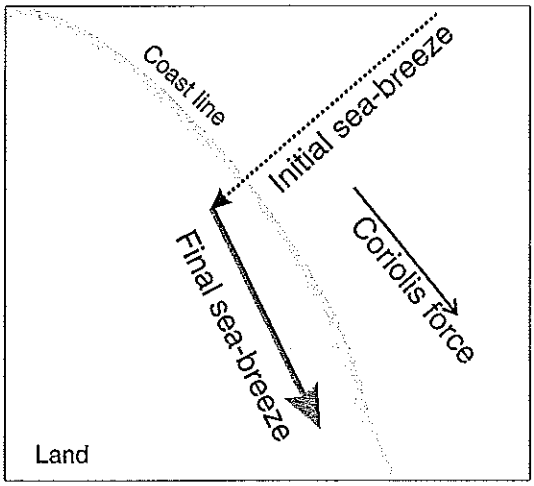


Figure 9.18
The Coriolis force can influence the direction of the sea-breeze over time.

and thunderstorms, particularly in the tropics where plentiful water vapour exists.

Dust devils may be observed along the sea-breeze front as illustrated in Figure 9.16. These small rotating columns of air should be avoided because they exhibit strong horizontal and vertical wind shear at low levels.

Prevailing winds may oppose the sea-breeze and delay its development, in some cases preventing it from reaching the land. If the prevailing wind is approximately in the direction of the sea-breeze, the resultant wind speed will be increased. On the other hand, the sea-breeze may take up a direction somewhere between that of the prevailing wind and the preferred direction of the sea-breeze. This is illustrated in Fig. 9.17, where the lengths of the arrows are proportional to the wind speeds.

As the temperature differences become greater in the early afternoon, the local pressure gradient between the sea and the land becomes steeper and so the sea-breeze increases. As a result, the impact of the Coriolis force is increased and the sea-breeze will end up flowing nearly parallel to the coast (Figure 9.18).

On a smaller scale, lake breezes may be generated by the same mechanisms as a sea-breeze.

Sea-breeze influences should be considered when selecting the operational runway at coastal aerodromes. The direction, strength and time of onset of the sea-breeze should be taken into account when planning take-off and approaches at airfields subject to sea-breezes.

9.11 Land Breezes

In coastal regions at night, land breezes may develop. These flow from the land to the sea. Radiation cooling from the land takes place much more rapidly than from the adjacent water. Eventually, the temperature of the land may fall below that of the water. The air in contact with the land then cools more rapidly than the air over the sea. The pressure at higher level above the land, then becomes

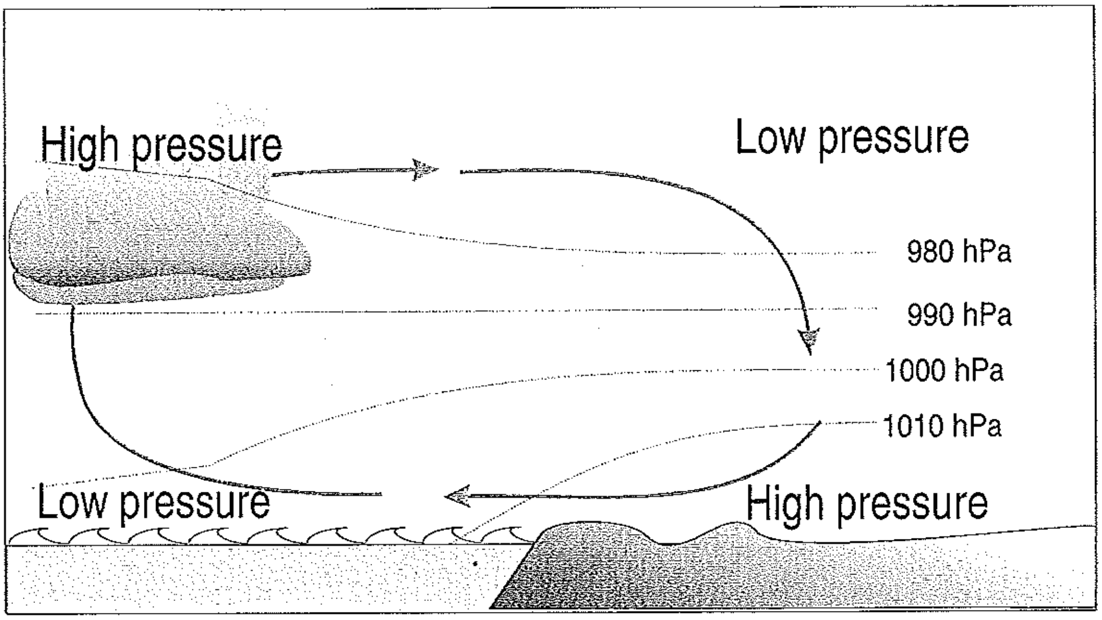


Figure 9.19
The structure of a land breeze circulation with high pressure over the sea and lower pressure over the land.

lower than that at the same level over the sea. As a result, the air tends to move from the sea towards the land at these higher levels. At sea level the situation is reversed. The pressure over the sea is lower than that over the land due to the transfer of air aloft. Consequently, the air in the lower layers tends to move from the land towards the sea, i.e. a land breeze will develop. The complete circulation is shown in Figure 9.19.

In general, land breezes are not as strong as sea-breezes. The temperature differences are smaller and so the local pressure gradient is weaker. Air rising over the sea may force moist air to rise, leading to showers or thunderstorms off the coast towards dawn.

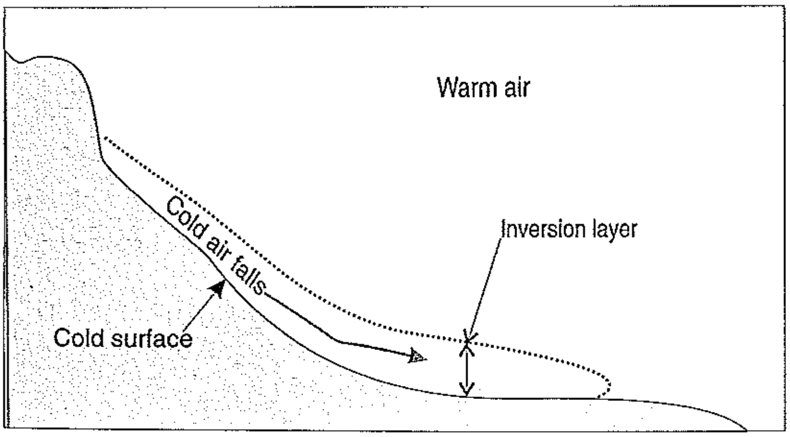


Figure 9.20
A cold layer of air falling down a slope (katabatic wind).

9.12 Katabatic And Anabatic Winds

When air over sloped terrain is cooled by conduction it becomes denser than near free air and drains to lower levels (Figure 9.20). The winds generated are known as katabatic winds. They depend on:

- the degree of cooling along the slope (the colder the surface, the greater the potential for the generation of very dense air and hence greater wind speed);
- the roughness of the slope (the smoother the slope the greater the potential for uninterrupted and thus stronger flow);
- the steepness of the slope (gentle slopes are more favorable for katabatic development because steep slopes cause the wind to become turbulent, resulting in mixing with surrounding air and the consequential breakdown of continual downward movement of cold air).

The reverse effect occurs on slopes on sunny days. Air in contact with a slope warms by conduction and ascends (not necessarily following the slope). Such ascending winds are called anabatic winds. The upward flow will be strongest in the early afternoon and over sun facing slopes.

9.13 Downslope Winds

Downslope winds are initiated by cool air from behind or above a slope falling to the base of the hill, spreading out and dissipating as gusty winds. Gusts at the foothills are often observed to be two to three times stronger than the prevailing wind and have been observed to 60 knots at some Australian locations. Turbulent and reverse flow winds are also observed for some kilometres downstream. They are more common in summer than winter and are strongest overnight and into the early morning.

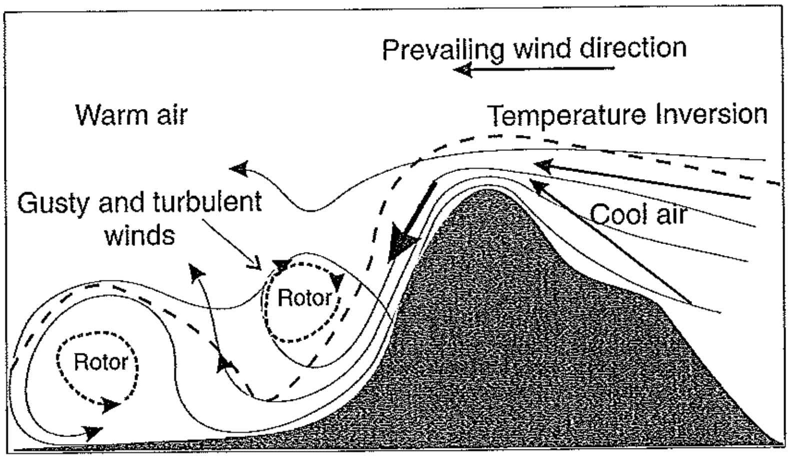


Figure 9.21
Gusty and turbulent winds generated by cool air, surging down a mountain slope into a warmer air mass on the lee side.

9.14 The Föhn Wind

When moist air is lifted by a mountain range, the air may saturate (cloud forms). If precipitation occurs on the windward side, the overall moisture content of the air passing over the mountain will be reduced. In consequence the cloud base will be higher downwind of the mountain and descending air will be drier and thus warmer. Figure 9.22 depicts this effect. The air rises at the DALR to the base of the cloud on the windward side of the mountain; it then initially cools at the SALR within the cloud before warming at the SALR to the base of the cloud on the leeward side. Below the cloud the air warms at the DALR. In this example, the surface air is 1.5 degrees warmer on the leeside than the windward side.

The significant features of the Föhn effect are:

- lower cloud base and precipitation on windward slopes;
- higher cloud base on lee slopes;
- higher temperatures and hence lower density at low levels in the lee of the mountain.

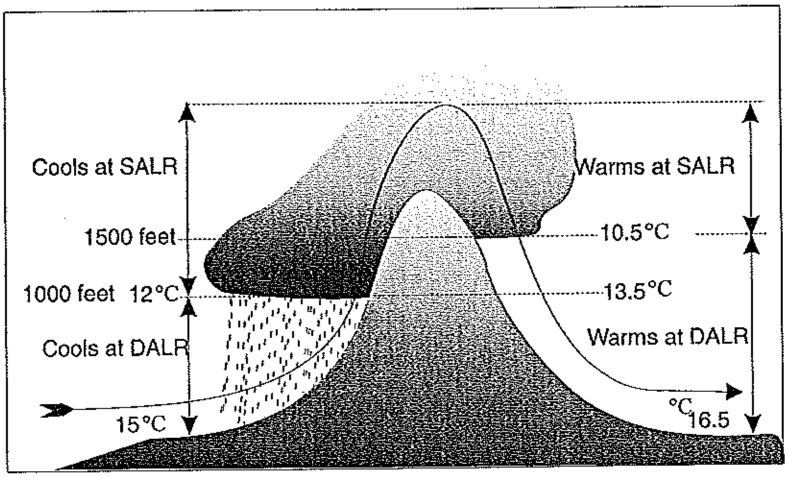


Figure 9.22
Cool moist air flowing over a mountain range with precipitation occurring on the windward side. The cloud base is higher on the lee side due to reduced moisture. Descending air becomes warmer on the lee side.

9.15 Obstruction To Wind Flow By Buildings And Tree Lines

Any obstruction to wind flow, including buildings and trees will produce disturbed air, manifested as wind shear and turbulence, that can significantly effect aircraft operations. Effects may become very marked in strong winds on the lee side of obstructions. Figure 9.23 shows some of the effects, which are:

- flow is disturbed to approximately three to four times the height of the obstruction (h) and 50 h downstream (beyond the scale of Figure 9.23);

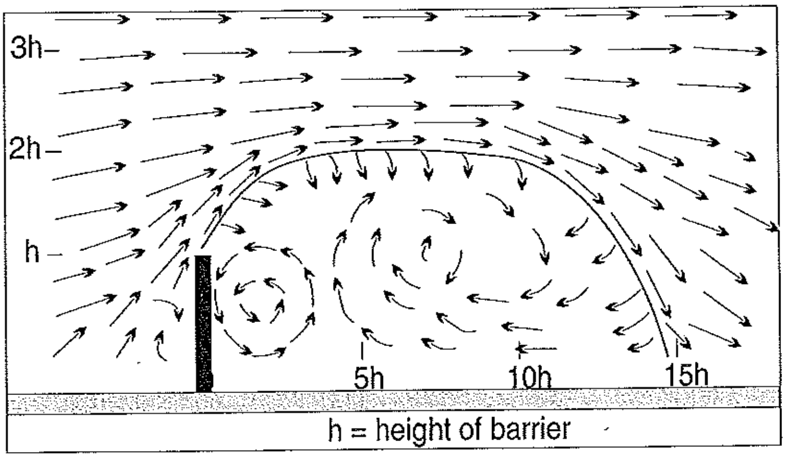


Figure 9.23
Airflow near a solid (impermeable) cross wind barrier (Note: The horizontal scale is different to the vertical scale).

- a cushion of air with weak eddies extends 2 h to 5 h upwind;
- wind is accelerated above and leeward of the barrier, the greatest increases in speed being at approximately 2 h to leeward and 2.5 to 4.5 h above the ground;
- strong eddies occupy the area up to 10 h to 15 h downwind to 2 h above the ground.

If the airflow passes through gaps in the barrier, such as with an open stand of trees, then the disturbance effects are greatly reduced. The eddy area in the lee of the barrier will be much smaller and usually does not extend above the height of the barrier.

These effects should be especially considered when landing or taking off in confined spaces in light aircraft, balloons, gyrocopters and helicopters.

The following excerpt from an ATSB report of a fatal accident highlights the danger.

> An examination of the wreckage indicated that the aircraft had impacted the embankment in a moderately nose-high, left wing-low attitude. Damage to the propeller indicated that the engine was delivering significant power at the time of impact. There were no known flight control deficiencies and the evidence indicated that the aircraft was capable of normal flight prior to the accident.
>
> Local procedures required that pilots conduct right circuits when operating on runway 19. Tall trees adjacent to the aerodrome induced localised mechanical turbulence, windshear and downdrafts when the wind was from the southeast. At the time of the accident, the wind was recorded on the Gold Coast Seaway as 150 degrees at 15 knots, gusting to 18 knots. It is likely that the aircraft entered an area of turbulence and high sink rate generated by the prevailing wind over the adjacent trees. Given the evidence of significant power at the time of impact, it is possible that the pilot had initiated a go around at a stage in the approach from which it was not possible to establish a positive rate of climb.

9.16 Obstruction Of Airflow By Raised Terrain

Mountain ranges obstruct wind flow in a similar manner to barriers such as trees and buildings but the effects are generally magnified. Ranges stop, deflect or disturb air flow depending on the speed of the air flow, the angle of impingement, the stability of the atmosphere and the structure of the range itself.

Disturbances are particularly noticeable when strong winds flow over, around or through rugged and steep terrain of significant elevation. Sometimes, even in moderate winds of 15 to 20 knots, airflow is significantly disturbed to great heights and turbulent eddies form in the lee of elevated terrain dangerous to aviation operations.

Blocking of wind flow

Wind flow at low levels (below ridge top), within a cool stable layer can be blocked by terrain of any height. Blocked (stalled) air can stagnate in front of terrain or flow at low level around it. Some low-level air may escape through valleys or over lower ridge tops.

Within the blocked flow, winds tend to stagnate or flow parallel to the terrain contours. This phenomenon is sometimes used to advantage to pilot hot air balloons along ranges even when oncoming prevailing winds are across the ranges.

Blocking has been observed windward of the Mount Lofty Ranges (in South Australia) when ridge top winds from the west have been as strong as 30 knots while below, at surface level have been observed to flow parallel to land contours (roughly northeasterly) up to 13 knots.

Blocking is depicted in Figure 9.24. It is most often observed to occur in the early hours of the day, before surface heating erodes the low-level inversion, thus decreasing stability at low levels.

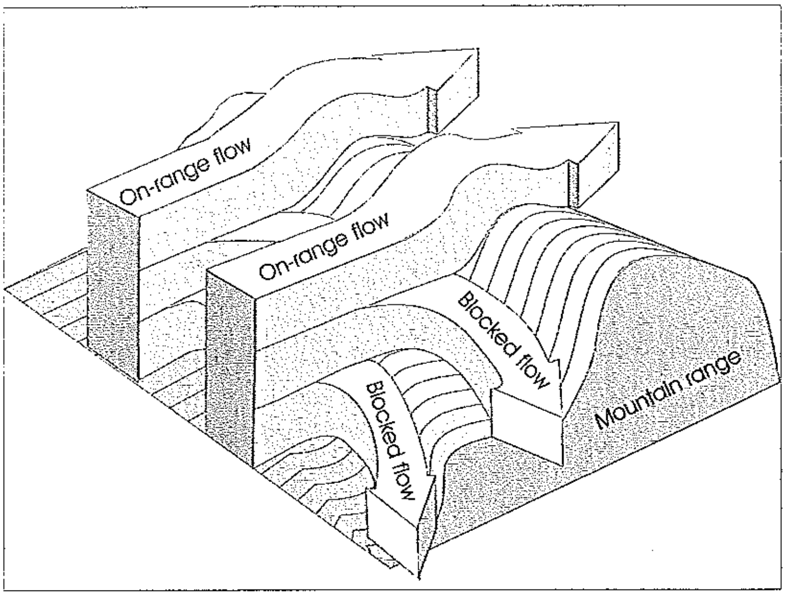


Figure 9.24
Flow approaching a mountain barrier. Lower stable layers of air, being denser than upper layers, flow along or around the barrier. The higher less dense air layers flow over the barrier.

Low level jets

Exceptionally high wind speeds sometimes occur at low levels in the early hours of the morning.

They are referred to as low-level jets because wind speeds, much greater than the pressure gradient and therefore the isobar spacing would suggest, are concentrated into narrow bands just above the earth's surface.

The jets occur when surface radiation inversions are strongest, i.e. in the early hours of the morning. The inversion is effective in shielding the flow above from surface frictional effects, allowing the wind speed to increase in a narrow stream near the top of the inversion.

The most broad-scale and persistent of these is the low-level nocturnal jet that extends over southern Queensland and the Northern Territory during winter. The maximum core of this jet is often located between Daly Waters and Tennant Creek (Figure 9.25) with a maximum speed around 50 knots above the surface but below 3000 feet, usually strongest around dawn and dissipating by 10 or 11am.

Low-level jets are not confined to the broad-scale as just described. They are frequently observed on a much smaller scale just ahead of cold fronts and along physical barriers such as hills and escarpments with the conditions of stability as already stated. Funnelling of the wind through valleys and ravines also produces similar effects on a local scale.

The wind shear and turbulence associated with the jets can be hazardous to light aircraft operating at low level and especially hazardous in the take-off and landing stages.

Mountain waves

Airflow over a ridge or mountain range may disturb flow downstream to a great height. It should also be noted that lines of thunderstorms present massive barriers to wind flow and can thus act to generate waves similar to mountain waves.

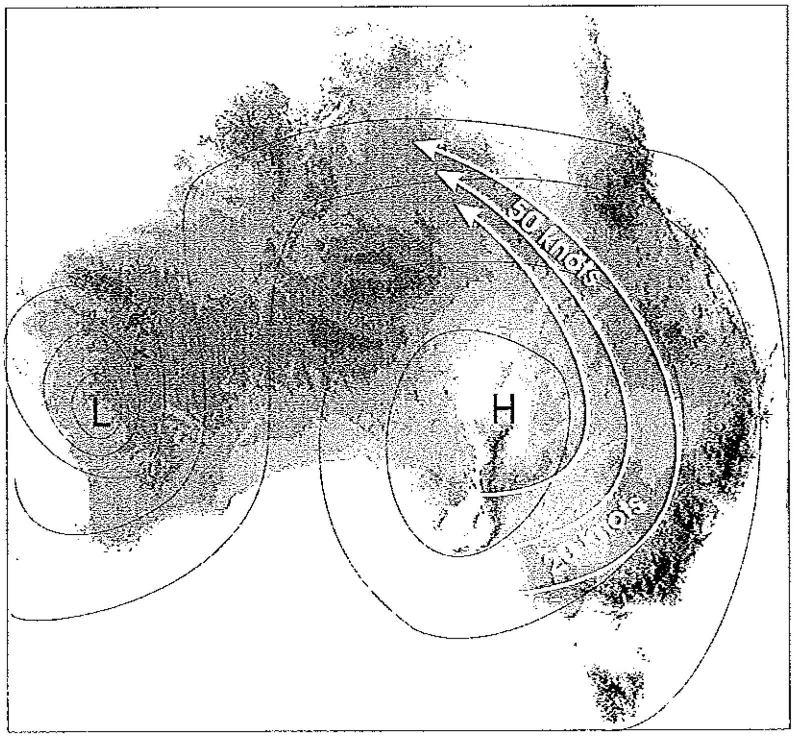


Figure 9.25
The orientation of a low-level jet above the surface but below 3000 feet.

Consider the situation of wind flow across a mountain ridge, as shown in Figure 9.26. The flow upwind of the ridge is smooth and horizontal. At the ridge line the airflow is lifted and follows the shape of the ridge. On the other side a dramatic change in the flow takes place. The flow does not return to horizontal flow but continues as a wave that may be smooth or may contain dangerous turbulent zones that are described in Chapter 10.

The conditions required for mountain waves, apart from flow near perpendicular to the mountain, are:

- wind strength of at least 25 to 30 knots near the mountain top;
- wind speed increasing with height;
- a stable layer.

If the air stream is sufficiently moist at any level, cloud may form in the ascending sections and produce almond or lens-shaped clouds called lenticular clouds. However if the air is dry the first indication of wave motion may be a rapidly increasing or decreasing altimeter reading.

Further discussion on mountain waves and related turbulence follows in Chapter 10.

9.17 Jet Streams

High speed, confined rivers of air called jet streams are most common in the vicinity of the tropopause. They can be of benefit to flights travelling in the same direction but hinder those travelling against the flow. They are frequently associated with turbulence (discussed in Chapter 10).

The World Meteorological Organization (WMO) has defined a jet stream as a strong narrow current, concentrated along a quasi-horizontal axis in the upper troposphere or in the stratosphere, characterised by strong vertical and lateral wind shears and featuring one or more velocity maxima. The speed of the wind must be greater than 60 knots.

A number of jet streams may occur at different latitudes and levels in the atmosphere as depicted in Figures 9.27 and 9.28. The jet streams of most relevance to aviation are the:

- subtropical jet stream (STJ);
- middle latitude jet stream called the polar front jet stream (PFJ).

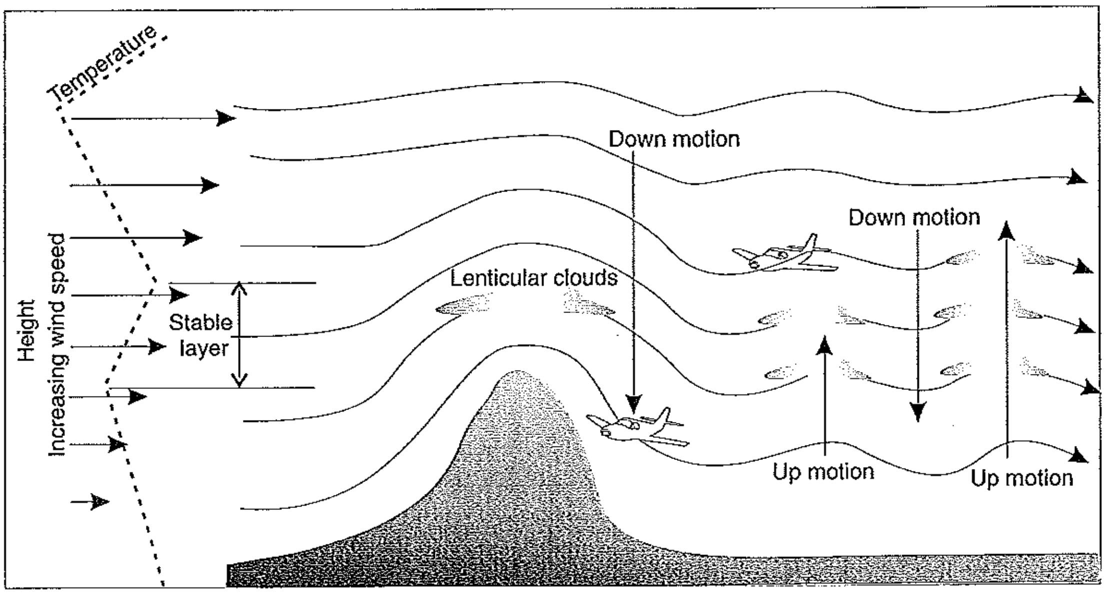


Figure 9.26
Smooth mountain wave formation is enhanced by a stable layer near the ridge top. Lenticular clouds can form in the crest of the waves (see Figure 10.8 for turbulence zones related to mountain waves).

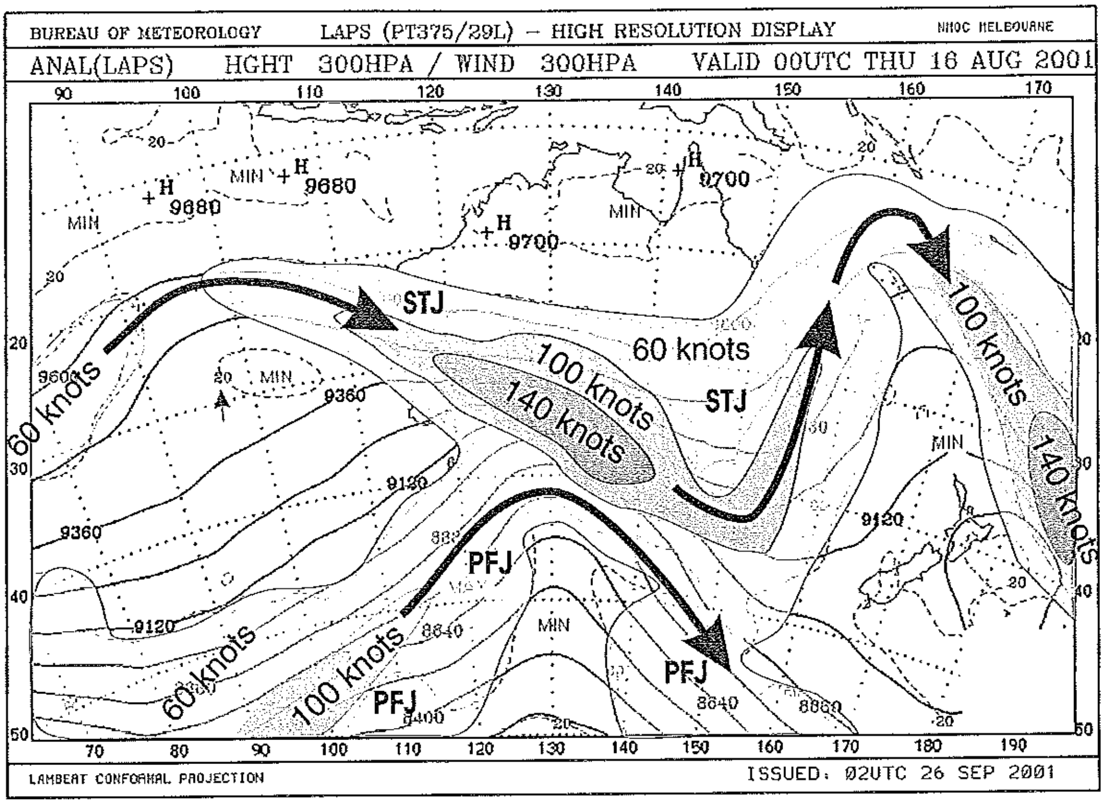


Figure 9.27
The diagram depicts a constant level 300 hPa chart with shading indicating the position and strength of the STJ and PFJ at 300hPa. Winds outside the shaded areas are less than 60 knots.

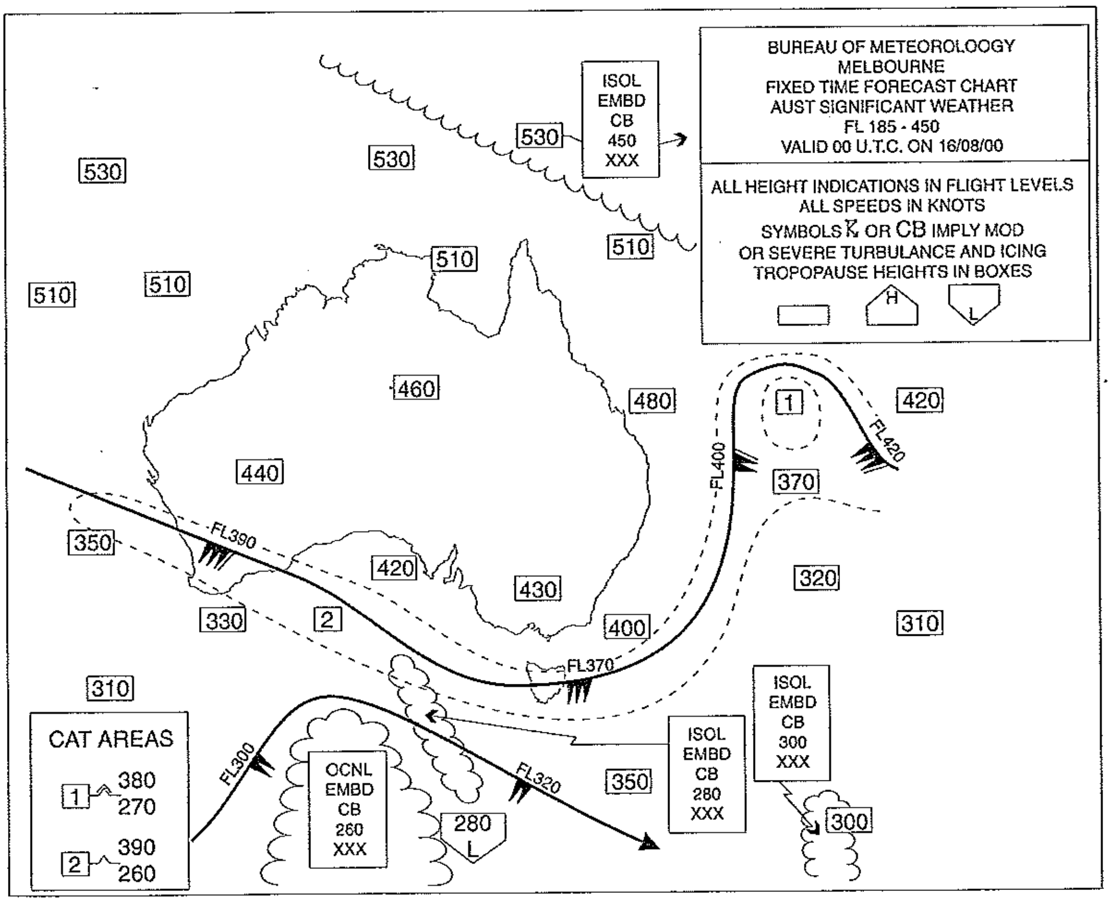


Figure 9.28
A SIGWX chart. Note the STJ axis varies in height ((given in flight levels (FL) and thousands of feet, i.e. FL390 = 39 000 feet)) from FL390, FL370, FL400 to FL420 across the Australian region while the STJ core varies from FL300 to FL320.

Subtropical jet stream

The subtropical jet stream is usually observed at about 40 000 feet (200 hPa), approximately vertically above the axis of the subtropical surface high pressure belt. This is located on average near latitude 30. It moves poleward in summer and equatorward in winter. The subtropical jet stream is not associated with a front in the lower troposphere. Typical speeds of the subtropical jet stream in the Australian region are about 120 knots, though the maximum can be over 200 knots.

Polar jet stream

The polar front jet is associated with individual outbreaks of cold air from the polar regions and occurs mainly in winter when it is often over the southern half of Australia or poleward of the Australian continent. When the PFJ is over Australia, the jet core tends to be at about 30 000 feet (near 300 hPa) with a typical speed of 80 knots. If the PFJ is south of Australia, the core is usually below 30 000 feet. A northwesterly PFJ will have a cold front associated with it, though weak cold fronts may not have an associated PFJ. A southwesterly PFJ usually follows the passage of a cold outbreak.

Note that the jet stream winds depicted in Figure 9.27 are for the 300 hPa only, and may not be representative of the maximum winds of the jet streams.

Jet core maximum wind speeds are depicted in Significant Weather (SIGWX) charts (see Figure 9.28). The SIGWX chart displays axis heights and speeds of jet streams and also indicates tropopause heights.

Jet streams can merge together into one broad belt of high speed winds. This feature is observed when the north moving polar jet encounters the northwest subtropical jet. They may also split, typically around high pressure systems.

TURBULENCE

Turbulence occurs when winds fluctuate rapidly over short distances. Fluctuations are sometimes so slight they have little affect on flight. However turbulence can make aircraft roll and pitch violently, and/or cause severe jolts, leading to loss of control, injuries to crew and passengers and to airframe damage.

The reactions of aircraft are dependent on their type, configuration and the speed at which they encounter turbulent zones. Aircrew and passenger reactions are compounded by the aircraft's response and the human reaction (physiological and psychological) to aircraft movement.

The five basic mechanisms that cause smooth flow to become turbulence are: convection, topography, Kelvin-Helmholtz waves, frontal zones and aircraft in flight (wake).

10.1 Convection

Turbulence associated with convection ranges from light thermal activity to extreme turbulence that may be experienced in mature thunderstorms.

When air is sufficiently moist, clouds form in thermals and give visible clues to the strength of the rising currents of air. On other occasions rising dust indicates the presence of thermal activity, but often thermals are active in clear air.

Within a single rising air current, flight conditions may be smooth, but turbulence is felt where there is a significant differential in vertical speeds, i.e. where one vertical current is rising quickly relative to adjacent air. When the adjacent air is descending, the difference is accentuated. Hence turbulence is usually most severe in and around mature thunderstorms that have strong updrafts and downdrafts associated with them.

Moderate or severe turbulence can occur near the ground in a mature thunderstorm due more to the mechanical effect of the cold downdraft than any low-level convection. Turbulence also occurs at high levels in cumulonimbus and sometimes even well above the tops. Further discussion of thunderstorm turbulence is covered in Chapter 12.

In large cumulus clouds, the strongest turbulence is usually found in or near the heavy precipitation.

Turbulence associated with thermal activity usually does not cause serious problems for aircraft, but the ride can be rough. While gliders seek out thermals to provide lift, light aircraft travelling at two or three times the speed of the glider may experience bumpiness sufficient to cause discomfort to passengers. Faster aircraft will experience more frequent bumps but will be in the turbulent area for a shorter time and the larger aircraft will have greater inertia due to larger mass to partially offset the extra bumpiness.

The flight path of a slow moving, light aircraft is shown dotted in Figure 10.1. A larger aircraft, at greater speed would experience smaller vertical variations and shorter, sharper bumpiness.

One aspect of thermal activity is the variability of currents caused by different surfaces and changes in the surface cover. On a warm day a ploughed field, because it heats

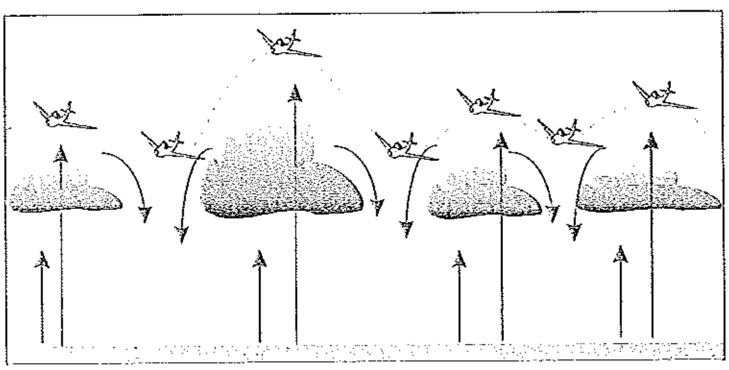


Figure 10.1
Deviations in the flight path of an aircraft as it encounters up and down motion in the vicinity of convective clouds.

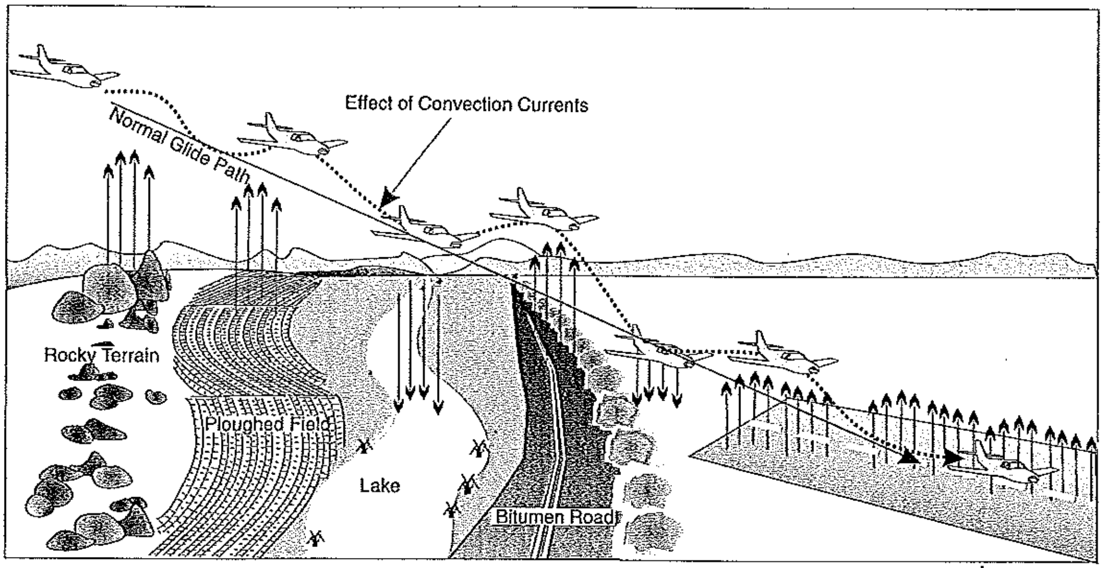


Figure 10.2
The desired path of an aircraft approaching an airfield compared with the actual path taken due to the affects of convection currents resulting from the heating of different surfaces.

more, produces stronger currents than green grass. Similarly a bitumen surface produces stronger currents than a water surface. These effects can produce changes in lift over a very short distance as illustrated by the deviation path shown by the dashed line in Figure 10.2.

Small-scale but extreme turbulence may be experienced in dust devils (rotating columns of warm air with central updrafts, made visible by rising columns of dust). These phenomena are often found over hot surfaces, when winds are light. High speed rotating winds may also occur at the intersection of sea breeze fronts or other regions where wind shear exists. Wind speeds within these compact phenomena commonly reach 30 knots but extremes of 50 knots have been recorded. Dust devils are generally short lived and have diameters of less then 30 metres or so. They may only reach a few hundred feet into the air. However, over desert areas in summer dust devils may extend to a few thousand feet and last for several hours. Figure 10.3 shows the near ground disturbances of thermally driven dust devils rising a considerable distance into the atmosphere.

When the atmosphere is deeply unstable, vigorous upward currents can 'punch' into the upper troposphere and lower stratosphere above cumulonimbus tops as illustrated in Figure 10.4. The action creates a wave well above cloud tops, somewhat like a bow wave traveling in front of a boat. Such waves can induce severe wind shear and turbulence across short boundaries in clear air. It is thought that a similar process generated the turbulence that caused the following incident.

On 6 July 1996 Qantas Flight 69, en route from Cairns to Tokyo, encountered severe turbulence at approximately 31 000 feet within the outer circulation of a developing typhoon. The incident occurred without warning as the aircraft was flying in clear air, and the on-board weather radar showed no returns in the vicinity. It lasted 30 seconds and produced accelerations greater than gravitational acceleration (-2.23g, +2.45g for a turbulent period of 2.125

Figure 10.3
Convective currents, rising into the air in the form of dust devils. High based fair weather cumulus clouds have developed in the rising air.
Photo©Inflow Images

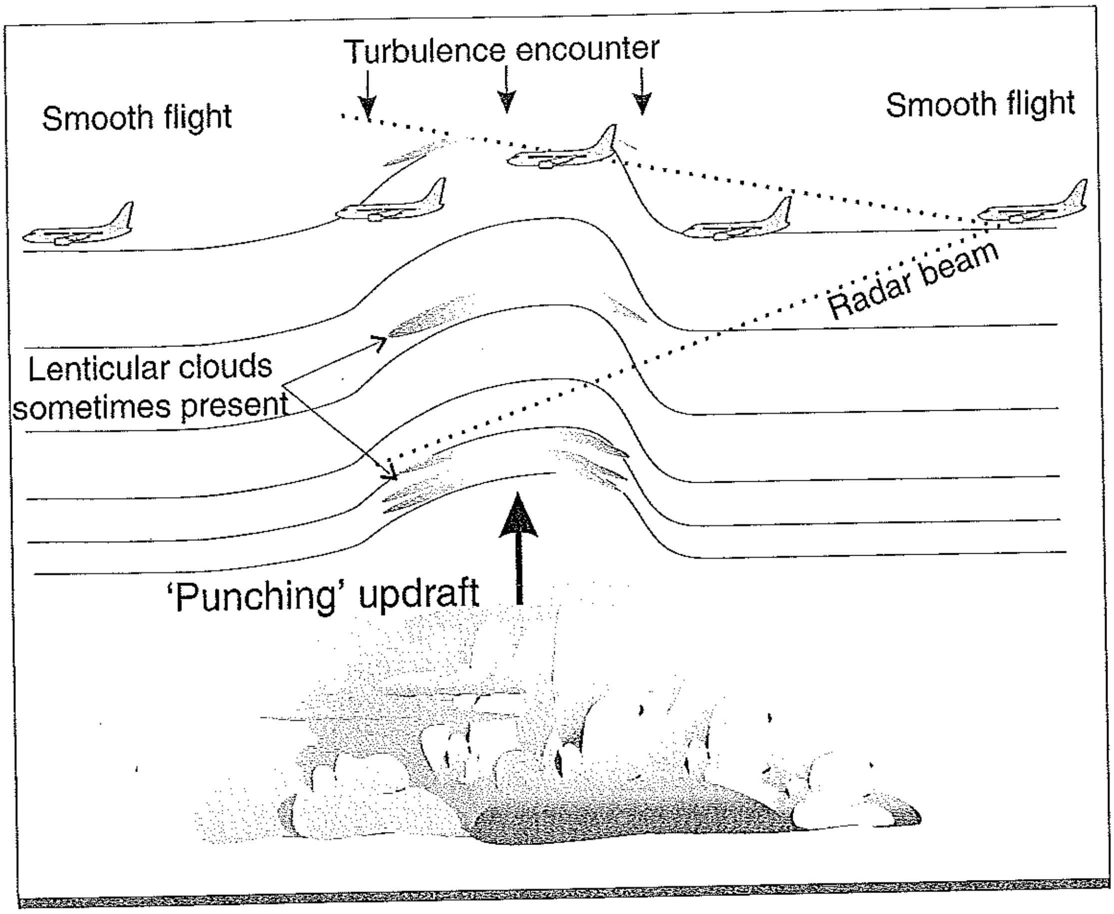


Figure 10.4
The diagram depicts developing cumulonimbus clouds with tops below the cruise level of an aircraft and out of radar range. Vigorous updrafts are generating atmospheric waves well above the cloud tops.

seconds) and resulted in 30 people requiring medical attention.

This case could well have been included in the Clear Air Turbulence (CAT) section of this chapter as the encounter was in clear air and 10 000 to 15 000 feet above cloud tops. Rather than being CAT as such, the incident is categorised as turbulence near thunderstorm tops (TNTT).

Conservative guidelines suggested to avoid TNTT (Pantley and Lester, 1990) are:

- avoid thunderstorm by 20 nautical miles (37 kilometres);
- do not fly within the anvil or in the thunderstorm tops;
- if flying over thunderstorms is unavoidable the distance an aircraft should maintain above the tops depends upon the wind speed. For a wind of 100 knots (at flight level) the distance should be 10 000 feet, for each increment of 10 knots above or below 100 knots, 1000 feet should be added or subtracted respectively.

A further guideline is to pass thunderstorms on the upwind side.

Mechanical turbulence can also be generated when prevailing winds flow over and around large cumulus and cumulonimbus clouds. The deviated winds combine with updrafts and downdrafts active within the cells to generate complex turbulent patterns (Figure 10.5).

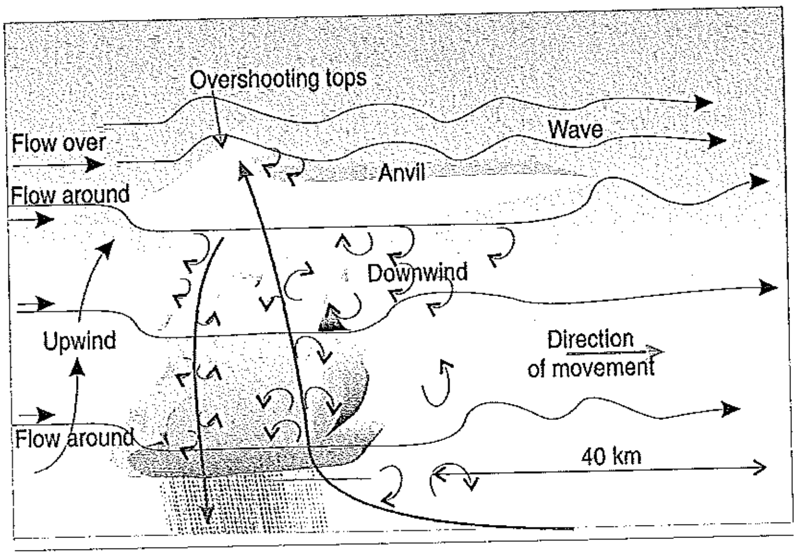


Figure 10.5
Turbulent winds within and around a large cumulus cloud.

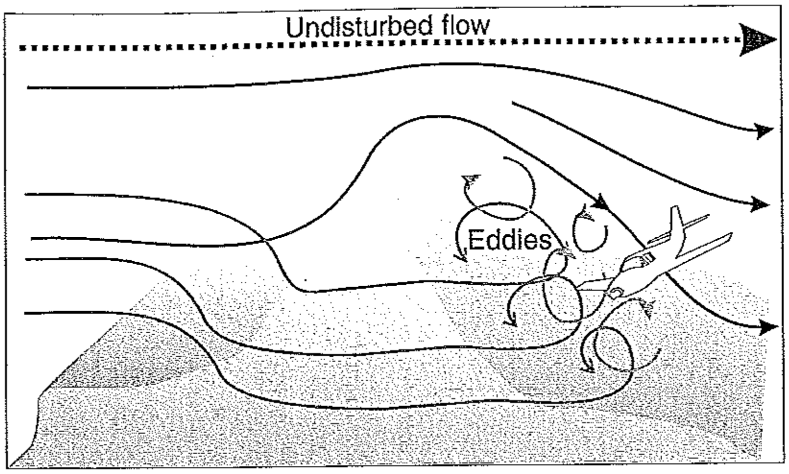


Figure 10.6
Wind flowing over and around a hill develops eddies on the lee side. Persistent and strong downdraft winds may be experienced to the lee of mountains even in the absence of mountain waves.

10.2 Topography And Orography

Obstructions to wind flow such as buildings, rough terrain and mountains produce turbulence of mechanical origin. Often the turbulence is contained near to the obstruction but at other times it propagates well downstream and well above the obstruction by way of wave motions.

The severity of mechanically induced turbulence and waves is dependent on the wind speed, atmospheric stability, and size and shape of the obstacle.

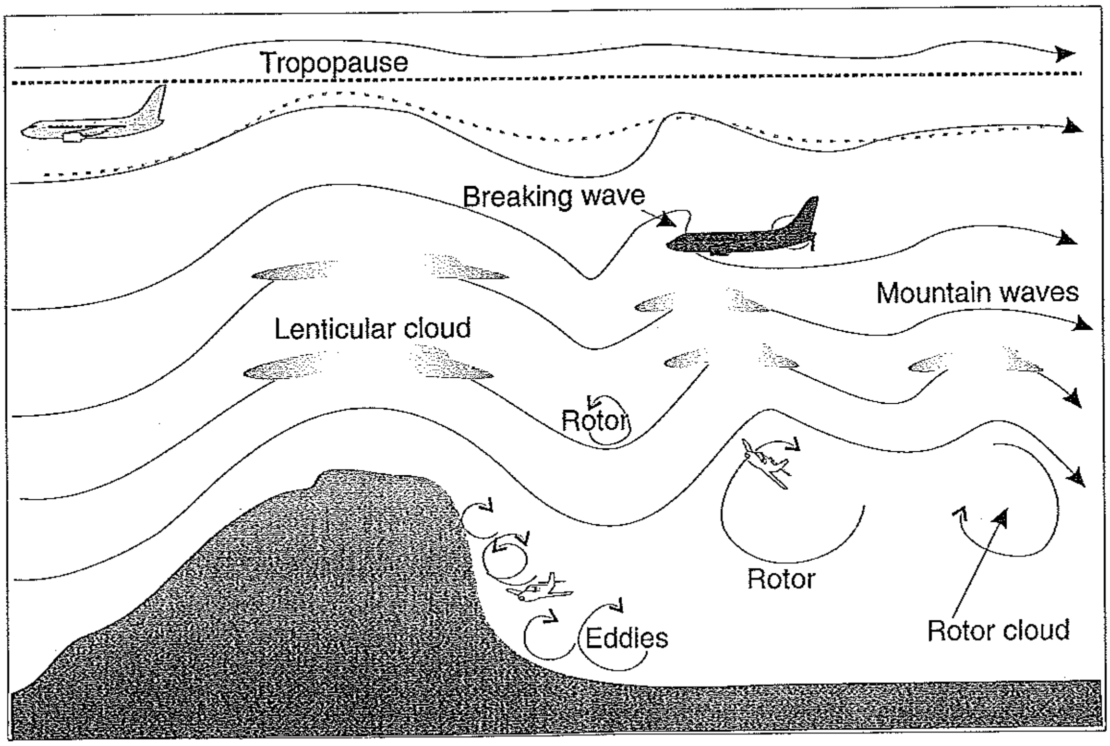
In the lee of mountain ranges strong winds produce down currents and turbulent eddies. The effects are magnified by steep terrain. Figure 10.6 depicts disturbed wind flow around a hill.

Aircraft approaching mountains, lines of trees or buildings from downwind need to ensure adequate clearance to avoid turbulence and downdrafts. A margin of at least the height of the hill or obstruction should be allowed.

The following incidents are testimony to the fact that adequate clearance should be maintained at all times when flying near hills:

- August 2001, The pilot of a helicopter was fatally injured when he lost control after the helicopter was damaged in severe mountain turbulence and crashed on the north slope of Mount Archer, Queensland;
- An aircraft flying in light turbulence and poor visibility near Cooma at 4000 feet began to lose height for no apparent reason. The pilot applied full power and put the aircraft in a climbing attitude. But, to his horror, there was no noticeable gain in height! The severity of the turbulence increased causing a wing

Figure 10.7
Wave formation propagating to the tropopause and well downstream of a mountain ridge with associated regions of wind shear and turbulence. Persistent strong winds and eddies in the lee of obstacles may also be present with mountain waves.



to drop as much as 35 degrees. As the aircraft continued to sink, at full power, the pilot noticed trees at about his level, the angle of attack was increased but the rate of climb was barely positive. The undercarriage hit treetops but fortunately the pilot recovered control and climbed out of trouble.

As already discussed, air often flows in complex ways over and around mountains and obstacles. At times variations can propagate well into the upper levels of the troposphere in the form of atmospheric waves. The waves can be likened to sea waves varying between very long, slow waves and very short, fast waves, depending on the shape of the mountain, the strength of the wind and stability of the atmosphere. Mountain waves (gravity waves) are among the most hazardous phenomena aircraft can encounter. There are often no visible clues to their presence, thus encounters can be sudden and catastrophic.

The waves can break and overturn just as ocean waves do as is depicted in Figure 10.7. Wave breaking can occur from a few thousand feet above the surface to the tropopause and possibly beyond. Resultant shearing generates severe turbulence of great danger to aircraft as illustrated by the following incidents:

• In 1992 a DC8 cargo jet suffered severe damage when it encountered extreme clear-air turbulence at 9.5 km (31 000 feet) over the Colorado Rockies. The jet lost an engine and part of a wing, but fortunately made a successful landing. It is believed that the aircraft encountered wave break turbulence or a horizontal vortex tube (HVT). HVT's are small scale (possibly less than 200 m wide) confined regions of turbulence generated when high-level jet streams and mountain waves interact. (Terry L. Clark and Lawrence F. Radke, 2001)

• In 1966, mountain wave induced turbulence ripped apart a BOAC Boeing 707 while it flew near Mt Fuji in Japan.

Rotors of whirling air sometimes form at the crest of waves. Severe turbulence can be associated with the rotors and is strongest in the first wave crest. If cloud is present it will appear as a ragged rolling cloud called a rotor cloud, depicted in Figure 10.7. The cloud will not be there in a dry atmosphere.

The presence of stationary clouds, formed in rows down wind of ranges, visually identifies wave motion and the potential for severe turbulence.

Wavelengths vary from 5 to 50 km.

Amplitudes depend on the size and shape of the mountain.

Vertical speeds may be more than 15 knots and have been measured at more than 40 knots. Large vertical currents are associated with:

- strong winds;
- large amplitude waves;
- short wavelength waves.

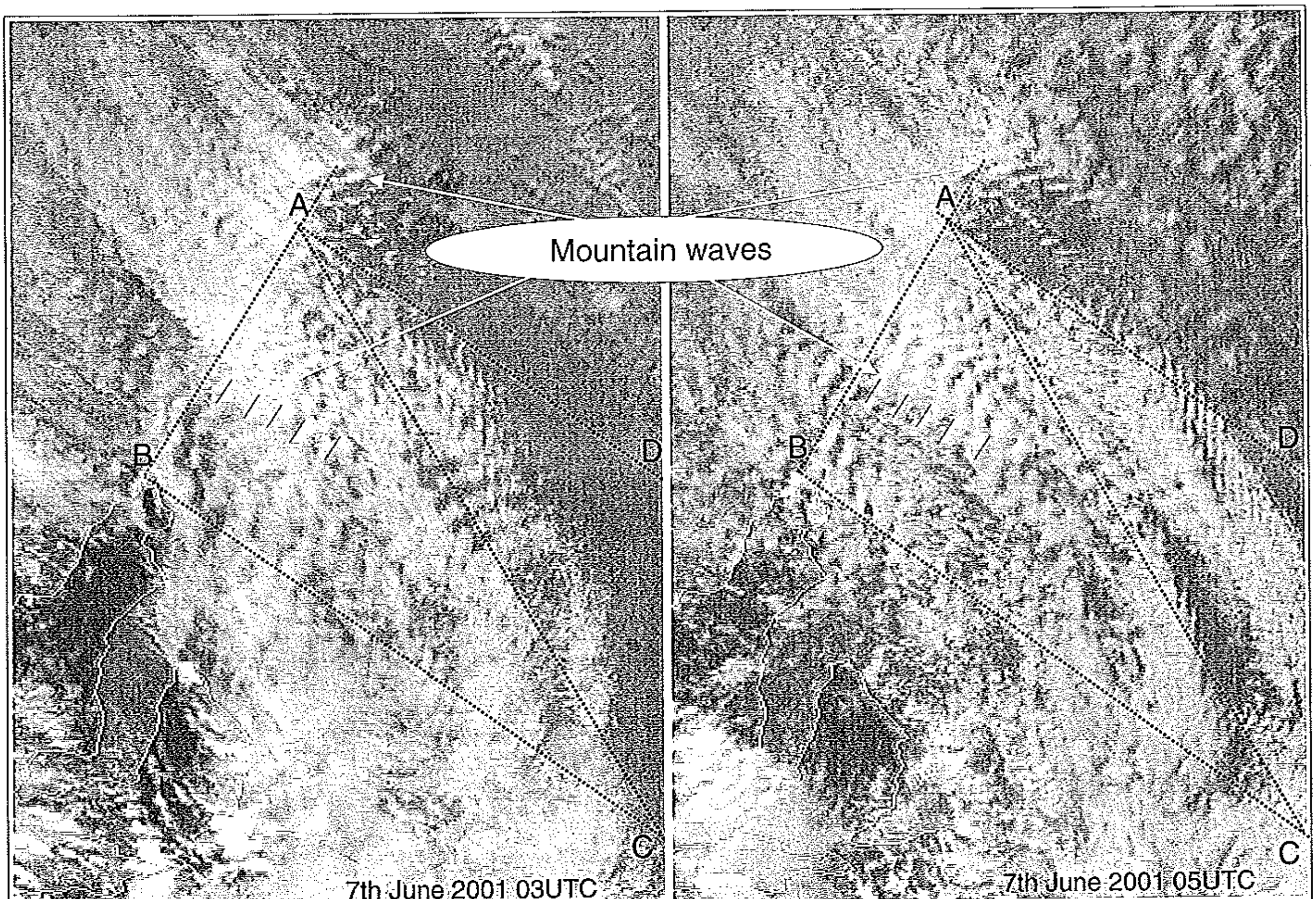
In Figure 10.8 a series of lenticular clouds can be seen lying parallel to the black line AB. They have formed at the crests of mountain waves. Five short black lines on the images mark some of the lenticular clouds that remained stationary over a two-hour period. While the marked clouds (and others) remain stationary over the two-hour period, other clouds move from left to right. The movement can be determined using grid BA, AD, BC and AC.

> In 1996, three people were fatally injured when a Cessna 206 encountered lee (mountain) waves. The investigation report concluded, "It is probable that the maximum climb performance rate of the aircraft was not capable of overcoming the strong downdrafts in the area at the time"(extract from an ASTB report).

Aircraft flying parallel to a range will experience continuous down or continuous up motion when waves are present. Should the pilot notice strong downdraughts, a quick diversion downwind will put the aircraft into a region of rising air. Glider pilots use this procedure to considerable advantage to establish high altitude records or to stay in the air far longer than possible with thermal activity.

10.3 Kelvin-Helmholtz Waves

In regions of marked wind shear where there is a significant change in wind speed across a small distance, Kelvin-Helmholtz waves may develop. It appears that friction between the air masses breaks the flow across the boundaries into short waves (much shorter than mountain waves) that can break and cause severe turbulence.



Satelite images of mountain waves five of which are marked with short lines

Figure 10.8

Two satellite images taken two hours apart. The grid lines between points A, B, C and D have been superimposed over the image for ease of tracking the movement of clouds. Note the stationary lenticular clouds marked with five small lines.

Cloud signatures known as Kelvin-Helmholtz billows sometimes show the presence of these waves. An example of these billows can be seen in Figure 10.9. The cloud pattern clearly shows breaking waves similar to those referred to earlier in Section 10.2. It is not unusual to see this pattern of cloud in low to mid levels of the atmosphere.

Turbulence associated with these waves is of most significance at high levels where it is frequently experienced in the vicinity of upper level jet streams. This type of turbulence most often occurs just below and poleward and just above and equatorward of the jet core (maximum wind speed), as illustrated in Figure 10.10.

The turbulence associated with Kelvin-Helmholtz waves is particularly dangerous to aircraft because it often occurs as CAT remote from topographic and convective influences. It is important to note however that this type of turbulence may also occur in the presence of cirrus (non-convective) cloud.

At times mountain waves interact with jet stream winds. The interaction forms confined regions of severe wind shear known as horizontal vortex tubes. They have the potential to produce severe wind shear and turbulence at high levels.

Figure 10.9

Kelvin-Helmholtz billows associated with wave motion, above a layer of fog. In this case fog has formed below an inversion in light winds. Sometime after fog formation, drier winds above the inversion have strengthened to a level where sufficient wind shear and subsequent turbulence mixes air across the inversion.

Photo©Gordon Garradd

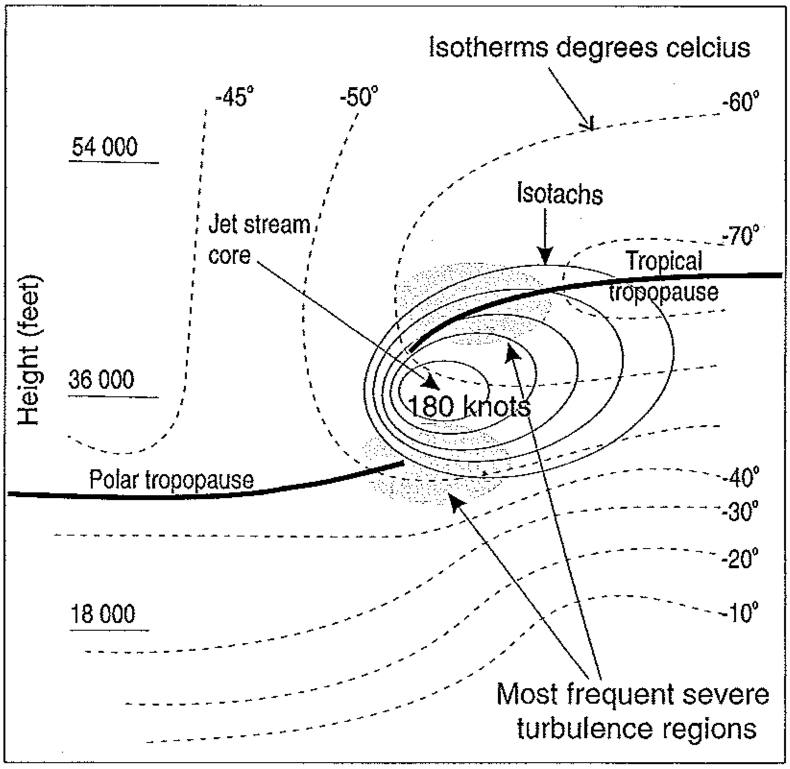


Figure 10.10

The jet core of 180 knots situated close to breaks in the tropopause and in the region of minimum temperatures (-50°C to -70°C). Potential severe turbulence regions are indicated by the shaded areas above and below the jet core.

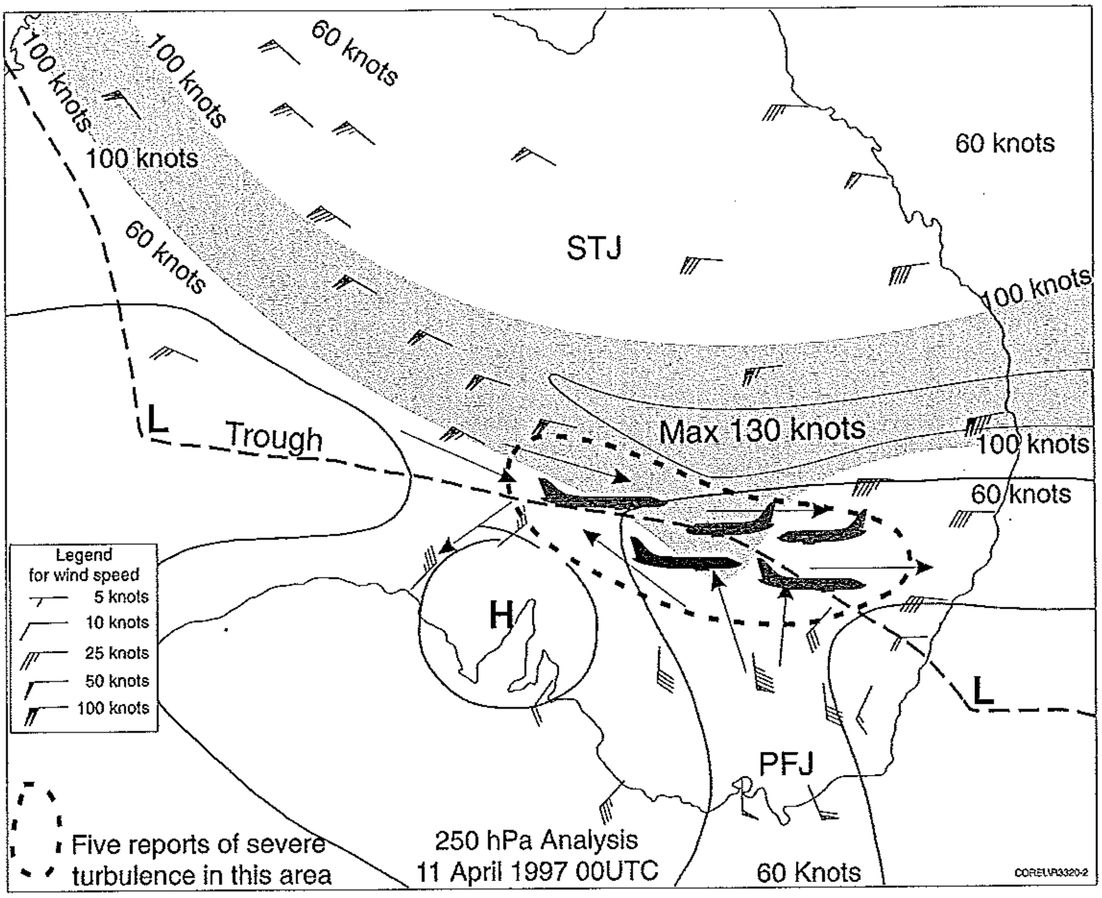


Figure 10.11
A 250 hPa analysis of wind speed associated with a subtropical jet stream (STJ) and a southern arm of a polar jet stream (PFJ) combining over southeastern Australia. A depiction of the height of the 250 hPa level shows high and low centres with a marked trough cutting across the continent. Severe turbulence reports were received from aircraft flying within the area designated by the short dashed lines encircling a portion of the trough. Note the sharp change in wind direction and speed across the trough; it is in this region that severe turbulence was encountered.

CAT can occur in the vicinity of upper level troughs (where wind shear is great) as illustrated in Figure 10.11. Here an upper trough has interacted with a sub-tropical jet stream to produce a very sharp gradient in wind speed and direction. In this case severe turbulence reports were received from five aircraft flying across the trough line. Note the jet core speed of 130 knots observed over Brisbane at this level (250 hPa) and the sharp variation of wind speed and direction across the trough line.

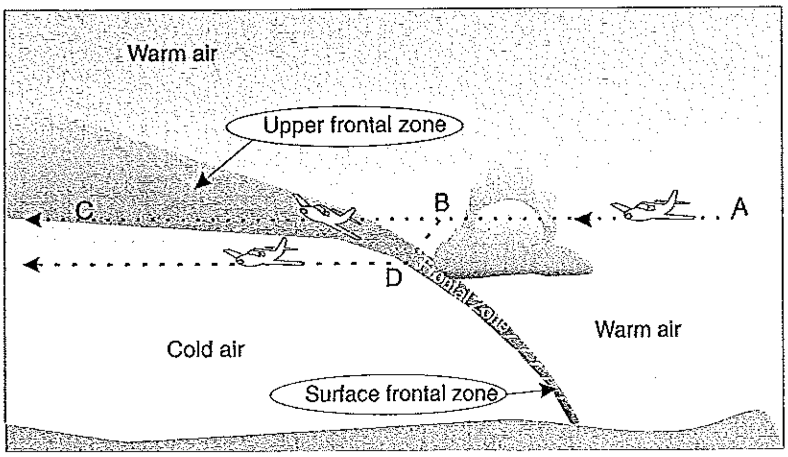


Figure 10.12
An aircraft changing flight level from B to A to avoid upper level frontal turbulence.

10.4 Frontal Zones

Frontal zones, including cold fronts and gust fronts from thunderstorms, may be associated with significant wind shear and turbulence. The intensity of turbulence in these regions is determined by:

- the speed of movement of the cold front or gust front;
- the degree of mechanical interference;
- vertical and horizontal wind shear across the frontal zone;
- storms generated on the front.

In vigorous cold fronts, a narrow zone of turbulent air will extend several thousand feet above the surface. In the absence of cloud and weather along a front, aircraft flying at low levels through this zone will encounter turbulence for only a short time. However, because frontal zones slope back and become broader with height, an aircraft flying well above and behind the surface front might be caught in a turbulent zone for some time. Figure 10.12 illustrates two possible flight paths. An aircraft with a planned route B to C could be caught in a turbulent zone for a long period of time, while an aircraft tracking B to D would experience turbulence for only a short time.

10.5 Wake Turbulence

All aircraft produce wake turbulence when aerofoils are producing lift. In order to produce lift, a pressure difference between upper and lower surfaces of the wing must exist. The pressure differences cause air to circulate around the wings and toward the wing tips. The circulations are then shed from the wing tips and evolve into a pair of counter-rotating vortices trailing behind the aircraft as depicted in Figure 10.13.

Each vortex is a mass of rotating air and consists of a core and a flow field about the core. When moisture levels are high enough, the cores of these spinning currents, which can reach speeds of 300 feet per second (180 knots), become visible, shooting from the wings as thin strands of condensed water vapor.

Aircraft encountering the powerful swirling vortices will experience some degree of turbulence, with short wingspan aircraft being most susceptible. At cruise levels encounters are unlikely to be severe but at low levels they are particularly dangerous to aircraft arriving or departing from airports, as the proximity to the ground means that any temporary loss of control could have devastating results.

> NEW YORK, Nov. 16 2001- Just after takeoff, American Airlines Flight 587 flew into the wake of a jetliner ahead of it. The plane shook, then hit a second wake before rattling again and plunging into a 20-second nosedive.

In calm wind situations the trailing vortices slowly descend and typically roll apart at about 2 to 3 knots as depicted in Figure 10.13 A. Cross winds can shift vortices over runways (Figure 10.13 B).

If the ambient cross wind counters the roll apart speed the upwind vortex may persist in the runway vicinity and continue to pose a threat for some time (aircraft-separation minima suggested by CASA of up to 3 minutes are indicative of the threat period) while the downwind vortex will move away faster – possibly toward parallel runways. Crosswinds of greater than 5 knots will push both vortices downwind.

Wake turbulence poses the greatest risk when ambient winds are light or calm. Atmospheric turbulence, generated by windy conditions, hastens the break down of vortices.

Under certain atmospheric conditions vortices may rebound off the ground (Figure 10.13 C). A tail wind can move the vortices forward into the touchdown zone.

The dissipation rate of the vortices, the path that they travel and whether or not they rebound or drift across runways is

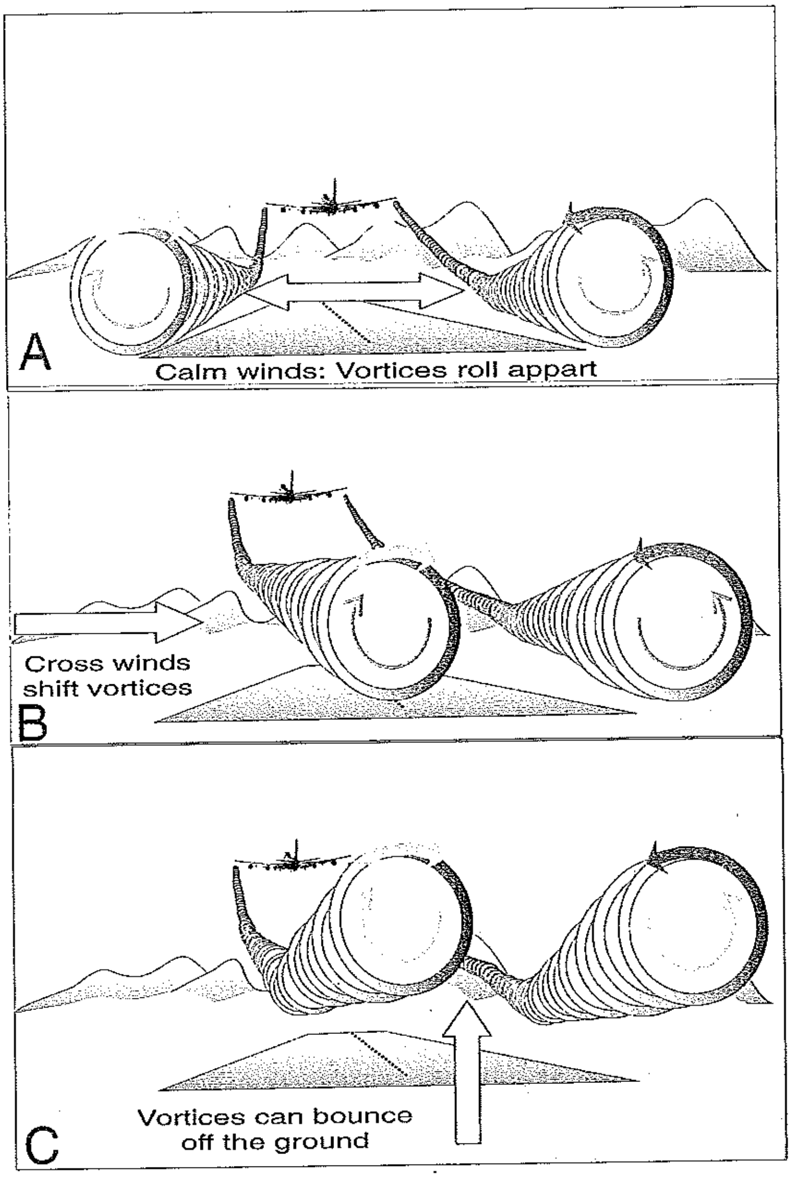


Figure 10.13
Vortices trailing behind aircraft. A, in calm conditions vortices roll apart. B, cross winds shift vortices across the runway. C, under certain conditions of atmospheric stability, vortices can bounce off the ground.

largely dependent on the atmospheric stability, wind strength, wind shear and turbulence.

Wake turbulence incidents continue to be reported at Australian airports (19 occurrences between 1998 and 2000). One incident occurred when a CL600 encountered the wake of a 737. The aircraft pitched up and banked 45 degrees causing the stall warning and stick shaker to activate, but fortunately the crew recovered control. There have been several reports of wake turbulence incidents causing momentary loss of control of flight, only evasive action by alert crews have prevented serious accidents.

Helicopters also produce wake turbulence. Helicopter wakes may be of significantly greater strength than those from a fixed wing aircraft of the same weight. The strongest wake occurs when the helicopter is operating at slower speeds.

The strength of the vortex is governed by the weight, speed and shape of the wing of the generating aircraft.

Typically, for each nautical mile behind the generating aircraft, the vortices will have descended between 100 and 200 feet. These vortices generally persist for up to 80 seconds over the runway, but in light or calm air this period may be up to three minutes.

10.6 Classification Of Turbulence

Turbulence intensity is specified according to the effect of the wind gusts upon the aircraft and its occupants as light, moderate, severe and extreme. A guide to these specifications is outlined in Table 10.1 below. Be aware that for a given turbulence situation, there will be a broad range of aircraft and passenger reactions, depending on the size, shape, weight, altitude and speed of the aircraft.

Intensity	Airspeed fluctuations (knots)	G-load (g)	Vertical gusts (feet per minute)	Aircraft reaction	Reaction inside aircraft
Light	5 - 14.9	0.15 - 0.49	300 - 1199	Rhythmic bumpiness. Momentary changes in altitude and attitude.	Little effect on loose objects.
Moderate	15 - 24.9	0.50 - .99	1200 - 2099	Rapid bumps or jolts. Appreciable changes in altitude and attitude.	Unsecured objects move. Appreciable strain on seatbelts.
Severe	=> 25	1.00 - 1.99	2100 - 2999	Large abrupt changes in altitude and attitude. Momentary loss of control.	Unsecured objects are tossed about. Passengers violently forced against seat belts.
Extreme		> 2.00	> 3000	Practically impossible to control aircraft. May cause structural damage.	Unsecured objects tossed about. Passengers forced violently against seat belts.

Table 10.1

A guide to aircraft reactions and in-cabin response to fluctuations in wind speed.

AIRCRAFT ICING

Ice accretion on aircraft remains one of the most significant meteorological hazards to safe and efficient aircraft operations. Every year many pilots experience serious reductions in performance of their aircraft as a direct result of ice formation on the airframe or within the engine induction system.

Aircraft flying through cloud in sub freezing temperatures are likely to experience some degree of icing. Parked aircraft are also susceptible to icing in cold conditions.

A pilot can lessen the chance of icing becoming a serious problem by de-icing parked aircraft, selecting appropriate flight routes, remaining alert to the possibility of ice formation and knowing how and when to operate aircraft de-icing equipment.
The following extract is taken from an ATSB report.

> The aircraft was en route from Albury to Melbourne, cruising at FL150. Approaching the Eildon Weir VHF omnidirectional radio range (VOR) navigation aid, the crew was instructed to hold for approximately 10 minutes. The crew reduced power to allow the airspeed to decrease to 154 knots, which was the selected holding speed. Prior to entering the holding pattern the speed fell below 154 knots. The pilot in command advised the co-pilot, who was the handling pilot, to monitor his airspeed. The co-pilot increased power and recorded data showed that the speed stabilised at approximately 144 knots. The co-pilot increased power a second time and the airspeed began to increase towards the target speed of 154 knots. The aircraft then passed over the Eildon Weir VOR. The co-pilot selected heading mode on the autopilot and set the outbound heading for the holding pattern. The airspeed at the commencement of the holding pattern was 149 knots. As the turn progressed the speed decreased from 149 knots to 141 knots over a period of 21 seconds. At that speed the aircraft began to vibrate and buffet and six seconds later, at an airspeed of 136 knots, the autopilot disconnected. One second later, at about 136 knots, the aircraft began to roll rapidly to the left, and started to pitch nose down, consistent with an aerodynamic stall. The pilot in command took control of the aircraft and regained normal flight at FL133.
>
> At the time of the occurrence the aircraft was in cloud, and icing conditions. The engine anti-ice and propeller de-ice systems were selected "on". The crew had not used the de-icing boots on the wings. The crew believed that an ice induced propeller imbalance had caused the vibration.

11.1 The Icing Hazard

Accumulation of ice can lower aircraft performance in many ways. It can:

- increase the stalling speed of the aircraft by changing the aerodynamics of the wing and tail as well as increasing the weight;
- make it almost impossible to operate control surfaces and landing gear;
- destroy the smooth flow of air over the aircraft;
- increase drag and decrease lift;
- cause engine failures;
- cause propeller vibrations;
- damage compressor blades of jet engines (chunks of ice can inject into the engine);

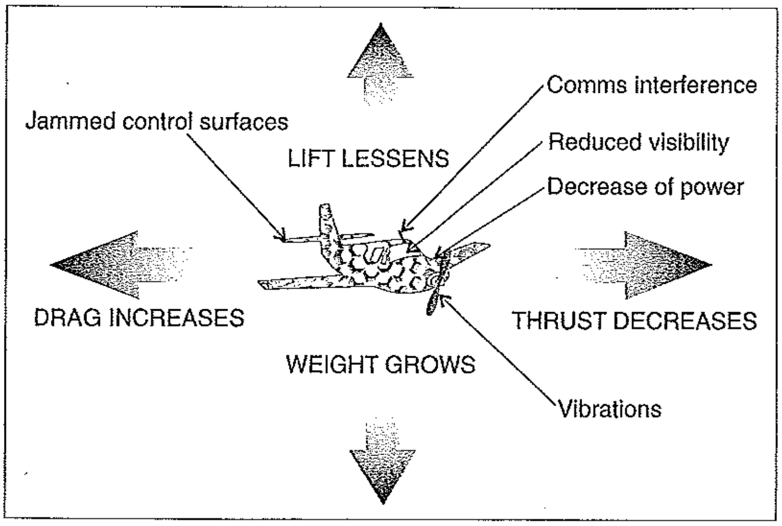


Figure 11.1
Some effects of icing on an aircraft in flight.

- produce errors in instrument readings of air speed, altitude and vertical speed;
- interfere with communication systems;
- reduce visibility.

Some of these effects are illustrated in Figure 11.1.

Wing and tail surfaces
Ice accumulations on wing and tail surfaces disrupt the flow of air around these aerofoils. Icing results in a loss of lift and an increase in drag causing the aircraft to stall at a higher airspeed than normal (see Figure 11.1). The weight of the ice deposit can also be important.

Experiments have shown that ice deposits of only one centimetre on the leading edge of aerofoils can reduce lift by as much as 50 per cent, increase the drag by an equal amount and thus greatly increase the stalling speed. It should be noted that deposits of one centimetre or more can accumulate in a minute or two in heavy icing situations.

Propellers
The accumulation of ice on the propeller hub and blades reduces the efficiency of the propeller. Increased power settings may then fail to produce sufficient thrust to maintain flying speed and more fuel is consumed. An even greater hazard is the vibration of the propeller caused by the uneven distribution of even a small amount of ice on the blades. Propellers with low revolution speed are more susceptible to icing than propellers with high revolutions per minute. Ice usually forms faster on the hub of the propeller than on the blades.

Helicopter rotors
Ice accumulations on helicopter rotors can be extremely hazardous because of reduced lift and the unbalancing effect caused by uneven ice distribution.

Drop-tip tanks
On jet aircraft, ice usually forms first on wing tips and, if fitted, drop tanks. Drop tanks are good collecting surfaces on other types of aircraft as well. The greatest effect of icing on these surfaces is to increase the drag on the aircraft.

Pitot tube and static-pressure ports
Icing of the pitot tube and static pressure ports may cause inaccurate airspeed and altimeter readings. When icing is observed on any part of the aircraft, the pilot should expect that the static ports are accumulating ice as fast or faster than other areas of the aircraft.

Radio antennae
The principal danger of ice accumulation on an exposed radio antenna is the probable loss of radio communication. Ice loading on the antenna may cause it to break and flail the fuselage.

Windshields and canopies
The formation of ice or frost on windshields and canopies is most frequent during takeoffs and landings, but it also occurs aloft.

Carburettor icing
Carburettor icing is the formation of ice in the throat of a carburettor caused by the sudden temperature drop due to fuel vaporisation and pressure reduction as air accelerates into the carburettor. The temperature reduction can be as much as 30°C with significant icing possible at temperatures well above 0°C. Carburettor heaters can eliminate the problem.

Fuel system

Turbine fuel absorbs a considerable amount of water when the air humidity is high. Sometimes icing of the fuel system can occur when flying in cold air where the fuel temperature is below the freezing temperature of water.

Induction system

Ice forms in the induction system in conditions favourable for formation of airframe icing. Induction icing can form in clear air too, when the relative humidity is high and the outside air temperatures are 10°C or colder.

Inlet guide vanes

Ice formation on the inlet guide vanes can reduce the airflow to the compressor and hence engine thrust. In severe cases the airflow reduction can be severe enough to cause a 'flame-out'.

Engine damage

The shedding of large ice accumulations from components ahead of the intake of jet engines can cause damage to the engine.

11.2 Icing Types And Causes

Two classifications of icing structural (airframe) icing and engine (induction) icing are discussed.

Understanding the causes of structural and engine icing requires an understanding of moist air and cloud formation as discussed in previous chapters.

Induction Icing

Induction icing refers to icing that interferes with the power plant of the aircraft and can occur at temperatures above 0°C. Its effects are described in section 11.1.

Structural icing

Structural icing refers to ice that accumulates on the exterior parts of the airframe and attachments such as pitot tubes and static ports. Structural icing occurs when water droplets present in cloud at temperatures less than 0°C (supercooled water droplets) freeze on impact with aircraft surfaces.

Ice forming on aircraft surfaces can be categorised as:

- clear or glaze ice;
- rime ice;
- a combination of clear and rime ice.

There is also another category that is usually associated with parked aircraft, namely hoar frost.

The size and temperature of the supercooled droplets that impact on the aircraft determine the category of ice that is formed.

Small supercooled water droplets freeze rapidly on contact with an aircraft's sub-zero surface resulting in a white, opaque deposit of ice with a rough lumpy appearance called rime. The opaque appearance is due to air trapped between individual ice particles, during the almost instantaneous freezing process.

Large supercooled droplets freeze relatively slowly on contact with an aircraft's subzero surface and tend to flow back over the surface resulting in a transparent sheet of ice which may be smooth or rippled called clear ice. The characteristics of clear and rime icing are discussed in sections 11.4 and 11.5.

An understanding of the water and ice structure of clouds with respect to temperature and cloud type will help a pilot identify meteorological situations with the potential for hazardous icing conditions.

11.3 The Icing Environment

The distribution of supercooled water droplets and ice within a cloud varies with temperature. Figure 11.2 illustrates the typical structure of supercooled water and ice in cloud with respect to temperature (Temperatures associated with icing type should be treated as approximate).

It is important to note the decrease in the number of supercooled droplets with decreasing temperatures.

Droplet size is also important. In general the largest supercooled droplets are found at altitudes just above the freezing level. The size of supercooled droplets tends to decrease with decreasing temperatures and/or increasing altitude.

Figure 11.2 relates the three most common temperature zones to icing type:

- 0°C to -15°C clear or glaze ice;
- -10°C to -15°C mixed clear and rime;
- -10°C to -20°C rime.

Note: These figures are approximate environmental air temperatures. Zones may overlap by about 5°C. Note also that rime may occur at temperatures colder than -20°C. At altitudes where the air temperature is colder than -35°C, supercooled water droplets are rare and the chance of ice formation is very small. In general, icing is not a significant threat at altitudes where the air temperature is colder than -20°C except in large cumulus and cumulonimbus clouds where strong updrafts can rapidly transport large supercooled droplets to colder altitudes.

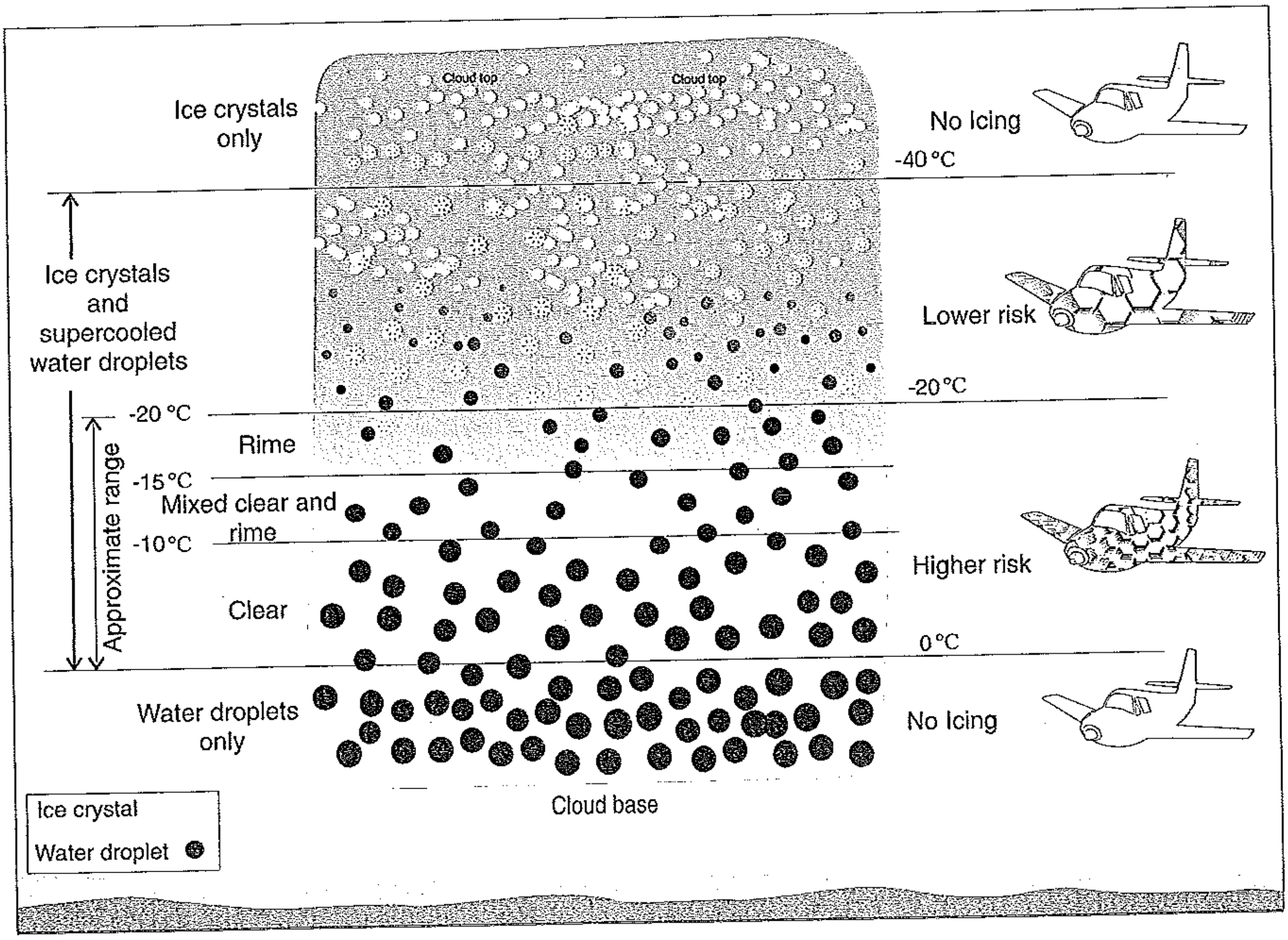


Figure 11.2
Water and ice structure of a cloud with likely approximate airframe icing and ice types. Zones may overlap by about 5°C.

The rate of ice accumulation is directly proportional to the amount of supercooled liquid water in clouds. The worst-case scenario involves large supercooled droplets, temperatures close to freezing and clouds with a large number of drops. This is most likely in large cumulus and cumulonimbus clouds.

Droplet size and numbers are characteristic of different cloud types. The relationships between cloud type and icing are:

- *stratocumulus* – occasional rime if freezing level is low enough;
- *large cumulus* – clear ice at altitudes higher than the freezing level;
- *nimbostratus* – moderate rime and clear ice probable in lower levels of the cloud; Beware of clear icing in freezing precipitation below cloud (refer to 11.11)
- *cumulonimbus* – dangerous clear ice;
- *altostratus* – light to moderate rime depending on cloud thickness. Clear ice possible in lower levels of the cloud;
- *altocumulus* – light rime.

11.4 Clear Icing

Clear or glaze ice is a transparent sheet of ice which may be either smooth (figure 11.3) or rippled. It most often forms in the temperature range of 0°C to -10°C.

Clear icing is probably the most dangerous form of icing, because its clarity can lead to the perception that surfaces are simply very wet, it adheres tenaciously to the surfaces on which it forms and the rate of accretion can be rapid, particularly on slower flying aircraft.

It is most commonly experienced in cumuliform cloud (where large supercooled water droplets are often encountered) and below cloud in freezing rain.

11.5 Rime

Rime is a white opaque deposit of ice with a rough lumpy appearance. While rime may be encountered between 0°C and -40°C it most frequently forms in the temperature range of -10°C to -20°C.

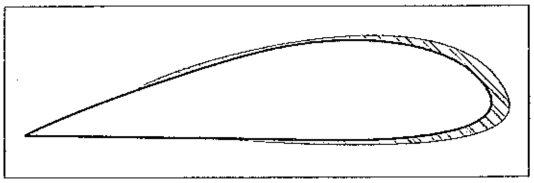


Figure 11.3
A cross section of an aerofoil showing clear ice adhering to the surface.

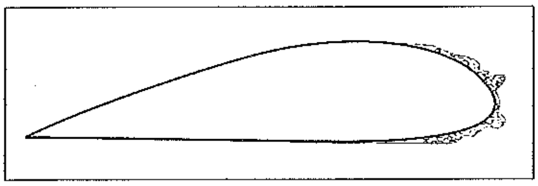


Figure 11.4
A cross section of an aerofoil showing rime adhering to the leading surface.

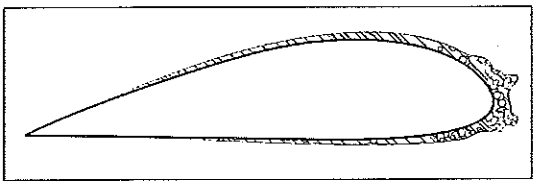


Figure 11.5
A cross section of an aerofoil showing clear ice and rime adhering to the surface.

As the droplet freezing process is almost instantaneous, rime tends to form on leading edges such as wings, fins, and air intakes (Figure 11.4) while the air bubbles trapped between individual ice particles account for its brittle nature.

The small supercooled water droplets responsible for rime formation are normally encountered in stratiform clouds between -10°C and -20°C, although it should be recognised that cumuliform clouds also may produce rime at temperatures below -10°C. In warmer temperature, deposits of rime are generally very slow to accumulate.

The main hazards posed by rime are distortion of the airflow and consequent reduction in aerodynamic efficiency of the wings, build-up of ice on the air intakes and blocking of pitot heads, static sources, and venturis.

11.6 Mixed Icing

As the name implies mixed icing is a combination of clear ice and rime. Its appearance varies but the rime component creates some degree of opaqueness. It commonly forms in the temperature range of -10°C to -15°C.

Mixed icing occurs when supercooled droplets vary in size or are mixed with snow or ice particles, a combination of clear ice and rime can rapidly form.

Mixed icing can lead to the formation of irregular shapes on airfoil leading edges as illustrated in Figure 11.5.

11.7 Hoar Frost

Hoar frost is a white, feathery, crystalline deposit of ice that forms by deposition on surfaces having temperatures below zero.

Hoar frost can form on an aircraft in flight when passing quickly from cold dry, to warm moist air. The water vapour in the warmer air can change directly to ice (refer deposition process 7.7). The ice will quickly disappear if the aircraft continues in the warmer air but in the interim formation on the windshield or canopy can severely inhibit visibility.

Hoar frost usually occurs in clear air when an aircraft is on the ground and its skin temperature falls below the frost point of the surrounding air (below 0°C). The weather conditions conducive to this are calm and clear nights. Under these conditions the surface of the aircraft, like a car, radiates strongly. Air in contact with the skin then cools (by conduction) to the frost point.

Frost should be removed from the aircraft before take off. Frost not removed in the pre-flight inspection can be dangerous, inhibiting visibility and modify the airflow over the wings so that the speed at which stalling can occur is increased.

11.8 Icing Intensity

Icing intensity ranges from trace, light, moderate to severe. These terms are defined below with reference to the potential danger:

- *Trace:* Ice becomes perceptible. It is not hazardous unless encountered for an extended period of time.
- *Light:* The rate of accumulation may create a problem if flight is prolonged in this environment.
- *Moderate:* The rate of accumulation is such that even short encounters become potentially hazardous.
- *Severe:* The rate of accumulation is such that short encounters are hazardous and immediate flight diversion is necessary.

11.9 Heating Of Aircraft Surfaces

The occurrence of aircraft icing is dependent on the temperature of the aircraft. Aircraft skin temperatures can be warmer than the environmental temperature due to compression heating at leading edges and frictional heating over the rest of the airframe. The faster the aircraft the greater the heating. At a true airspeed of 500 knots the effect may be as much as plus 25°C.

11.10 Orographic Effects

The effect of mountains on air movement is likely to cause an increase both in the depth of a cloud layer and the liquid concentration within the cloud. Icing may therefore occur more rapidly over mountainous terrain. Its severity will be increased if frontal systems are also in the vicinity.

11.11 Freezing Rain

One of the most severe forms of clear icing occurs when an aircraft below cloud base encounters supercooled rain or drizzle. This phenomenon, known as freezing rain or freezing drizzle, may result in an aircraft becoming enshrouded in a clear ice layer in a matter of seconds.

Such conditions can occur ahead of a warm front or sometimes behind a cold front when warm moist air aloft overruns sub-zero air at lower levels. Rain falling from or through warm air into sub-zero air can become supercooled. On impact with an aircraft the supercooled raindrops flow over exposed surfaces and freeze as clear ice.

The most severe icing occurs near the top of a shallow cold layer beneath a thick layer of warm air. The supercooled raindrops are much larger than cloud drops and thus lead to rapid accumulation of clear ice.

Figure 11.6 illustrates a wedge of warm air penetrating into sub-freezing regions around a frontal system. Rain falling into sub-zero conditions is cooled and modified to freezing rain conducive to the formation of clear ice on aircraft.

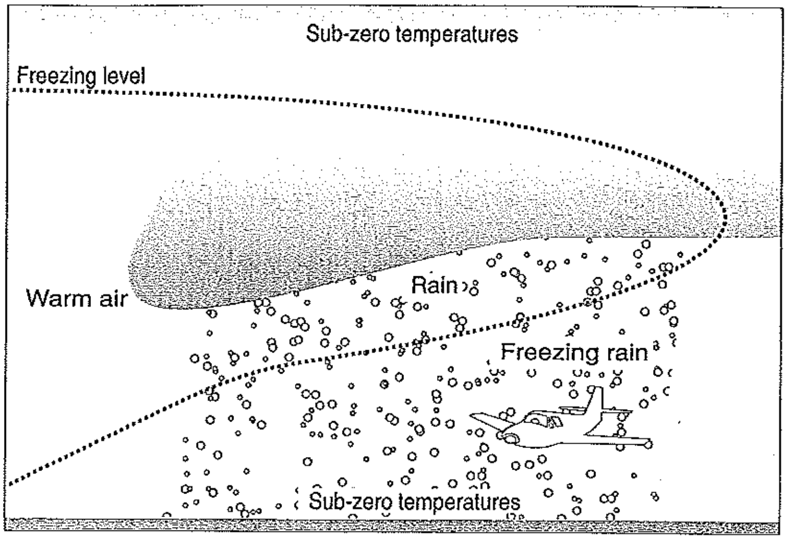


Figure 11.6

Freezing rain beneath a wedge of warm air at a frontal zone. Accumulation of clear ice can be rapid in these conditions.

11.12 On-Ground Icing

On-ground icing is common in Northern Europe and Canada and less common in Australia. However, on-ground icing conditions have been reported and have been the cause of airport closures at a number of Australian locations including airports in Tasmania and in the higher areas of New South Wales and Queensland. Tullamarine in Victoria has been closed for several hours due to the possibility of ice having formed on parked aircraft.

Failure to inspect and clear ice from parked aircraft before flying can pose serious risk to the safety of operations. Although no known fatalities have occurred in Australia some infamous accidents have claimed passenger aircraft overseas when captains have elected to take off before clearing ice and snow from their aircraft as reported in the August 2002 Aircraft & Aerospace magazine as follows.

> As the jet began its take off roll the captain assumed snow would blow off the wings as the jet built up speed. But it did not build up enough speed. The temperature on the upper surface of the wing mimics a refrigerator, in that the partial vapour pressure created on the top of the lifting surface causes the air to cool further, making the snow crystals bond to the surface like stucco cement, and compromising its aerodynamic efficiency with every grudging increase in speed. The doomed Air Florida flight became airborne riding on the ground effect of a cushion of air compressed below the wing, but as the captain panicked and pulled the nose up this was lost. Engines screaming, the jet began to sink back to the ground before spearing into the Potomac River.

Besides losing aerodynamic lift there is also the danger of ice jamming control surfaces.

THUNDERSTORMS

In regions where the troposphere is sufficiently moist and unstable and where there is a lifting mechanism to initiate convection, convective clouds can grow to great heights and develop into thunderstorms. Thunderstorms are convective clouds (or aggregations of convective clouds) in which electrical discharge can be seen as lightning and heard as thunder.

Thunderstorms consist of one or more dynamic building blocks called convective cells. A cell is a compact region of relatively strong upward air motion and has a distinct life cycle.

12.1 Thunderstorm Cells

There are two basic types of thunderstorm cells, the ordinary and the supercell.

The ordinary thunderstorm cell
Most thunderstorm cells are of this type and form in an environment of weak vertical wind shear. This type of cell is normally 5-10 km in horizontal extent and usually short-lived in its mature stage (15-30 minutes) due to its updraft becoming exhausted of moisture. It has been observed that the ordinary thunderstorm cell can sometimes produce severe weather for a short time if the updraft or downdraft is strong enough.

The supercell
The supercell is a larger (10-40 km across), more organised convective cell that forms in a suitable environment of strong vertical wind shear, strong instability and large moisture supply. The supercell can last for several hours (up to seven hours has been observed) in its mature stage because of the way in which it interacts with the environmental vertical wind shear to maintain a strong, deep, persistent, rotating updraft of moist boundary layer air. Although relatively rare, the supercell has the capacity to produce extremely severe weather.

12.2 Thunderstorm Structures

The ordinary cell is the most common component of single cell or multicell thunderstorms. Supercells tend to occur on their own but can occasionally be present in multicell thunderstorm systems.

Non-severe storms usually exhibit short lifetimes of an hour or less, and occur typically in environments with weak vertical wind shear. They may occur as a single cell or as a small cluster of cells.

The Bureau of Meteorology defines severe thunderstorms as being associated with one or as more of the following phenomena:

- heavy rain and flash floods;
- hail with diameter equal to or greater than two centimetres;
- tornado occurrence;
- wind gusts equal to or greater than 48 knots.

Storms meeting these criteria are not uncommon in Australia. They do not have to be large or long-lived to produce severe weather.

Visually, it is difficult to pick the storm that will produce severe weather. All thunderstorms have the potential to be a hazard to aviation no matter what their size. Some types of thunderstorms known to be severe include:

- pulse severe thunderstorms;
- cool season thunderstorms;
- the organised multicell thunderstorm;
- thunderstorms associated with convective systems and complexes;
- squall line thunderstorms;
- supercell thunderstorms.

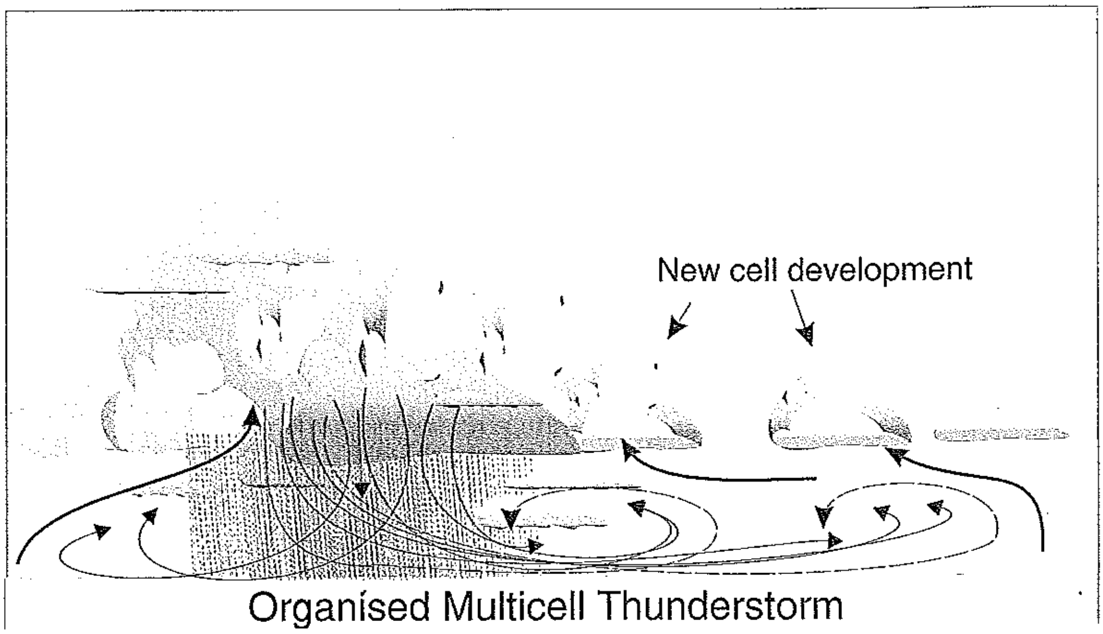


Figure 12.1
A multicell thunderstorm with characteristic outflow lifting previously unaffected air to saturation in the vicinity of the original cell. Close knit organised multiple cell storms may be initiated in this way.

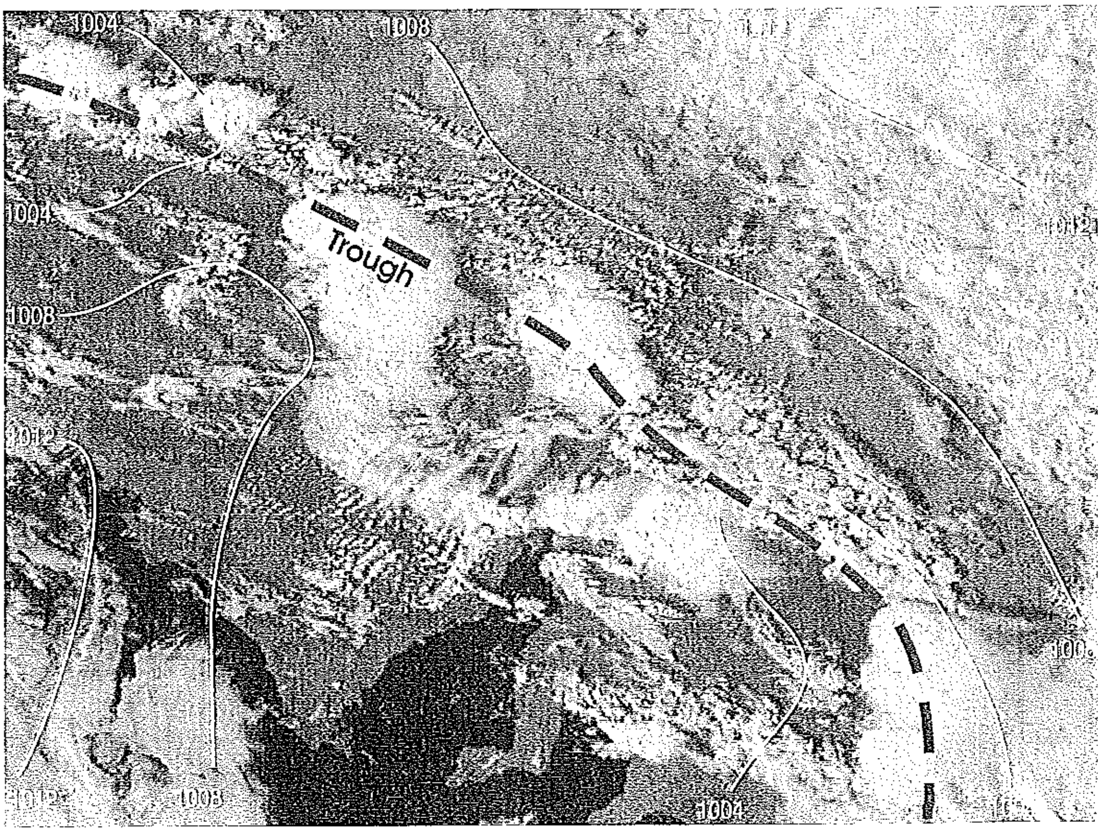


Figure 12.2
Clusters of thunderstorms forming in the vicinity of a convergence zone, along a trough of low pressure, illustrated by a satellite image with a synoptic chart overlay. In the lower right hand area of the satellite image a complex of three storms can be seen. Note also the series of storm complexes along the trough line and the huge areas they affect.

Pulse severe storms
These are ordinary cells that produce a short pulse of strong updraft or downdraft. Pulse downdraft severe storms are of particular interest to aviation due to their association with downburst and microburst activity. Downdraft storms are subdivided further into:

- Wet Downburst Severe Storm. Downbursts occurring in the vicinity of heavy showers;
- Dry Downburst Severe Storm. Downbursts occurring below virga (rain not reaching the ground).

Downburst effects are discussed later in this chapter.

Cool season severe thunderstorms
Cool season thunderstorms are frequently observed in southern Australia to produce damaging straight-line winds and sometimes tornadoes. These storms are smaller than their warm season counterparts and exhibit weaker radar signatures (refer to Chapter 16), but they have essentially the same structure. Cool season severe storms are observed to form along cold fronts or pre-frontal troughs or occasionally in the cold air behind a front, in environments exhibiting only moderate buoyancy but strong vertical windshear.

The Organised Multicell Thunderstorm
Organised multicell thunderstorms consists of two to six ordinary cells. The degree of organisation of this thunderstorm type gives it a relatively long life and a greater chance of producing severe weather over a broad area, difficult to navigate around. It tends to form in environments with moderate vertical windshear. Such an environment encourages strong low-level storm-relative inflow and gust-front convergence, leading to repeated new cell growth. Figure 12.1, 12.10 and 12.11 illustrate how downdrafts from one cell or group of cells can lift moist air and spawn new cell development.

Convective systems and complexes
Convective systems and complexes consist of a large number of cells (clusters) at various stages of development, organised either as a large cluster of thunderstorm cells or as a squall line (discussed later). These thunderstorm systems are capable of producing severe weather, especially flash-floods, hail and strong downdrafts. Such cloud systems may exceed 500 km in diameter.

Squall lines
Squall lines occur when cells are arranged in long lines (frontal or non-frontal) and adjacent cells are so close together they form line thunderstorms. Such storms are often accompanied by strong surface wind gusts; hence the name squall line. Mid-latitude squall-line thunderstorms are observed regularly over parts of southern Australia and sometimes produce severe weather.

Squall lines develop initially along a linear lifting mechanism such as low pressure troughs, along the intertropic convergence zone or with significant wind shear regions with other convergence producing weather systems which may be a front but is more likely to be a pre-frontal trough as depicted in figure 12.2.

Squall lines can be particularly dangerous to aircraft in flight since they can present a wall of severe weather difficult to penetrate safely and too wide, high and long to negotiate. Cloud bases can change rapidly and are often very low, so flying beneath the cloud, with a good chance of encountering strong downdraughts, hail, rain and poor visibility, severe turbulence and low cloud is a potentially hazardous procedure.

Supercells
In some storms, the balance between buoyancy and wind shear approaches an optimum, leading to the development of long-lived thunderstorms (several hours) with strong rotation within their cores. These storms are known as "Supercells" and are responsible for the majority of damage caused by severe thunderstorms. Supercell thunderstorms may produce very large hail, extraordinary wind gusts, powerful tornadoes and heavy rainfall. These supercells may develop rapidly from an ordinary cell or line of cells and move off in a different direction to other thunderstorms in the vicinity.

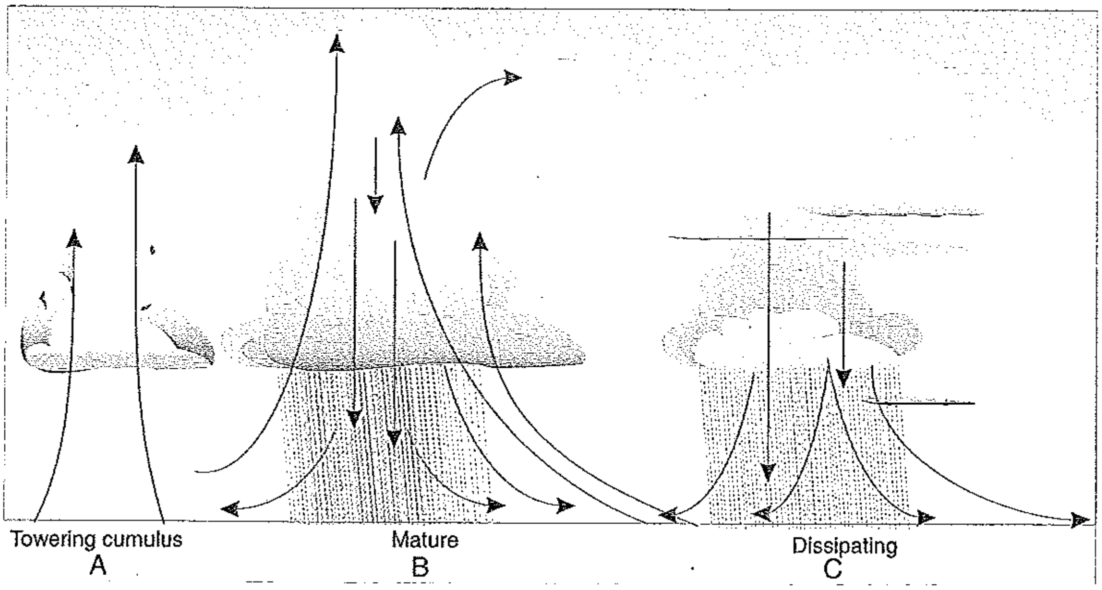


Figure 12.3
Stages in the life cycle of a single isolated thunderstorm cell. At A the developing cell is dominated by updraft. At B the mature cell is producing precipitation and downdraft has developed next to the updraft. This is the most intense phase of the cell with respect to draft speeds, precipitation, lightning, etc. At C the dissipating cell shows only weak remnants of updraft, being dominated by downdraft as a pool of rain-cooled air spreads out at the surface, choking off the updraft. Note the erosion of cloud in the downdraft area. A single cell takes approximately 40 to 60 minutes to go through this life cycle.

12.3 Life Cycle Of An Ordinary Thunderstorm Cell

The life cycle of the ordinary thunderstorm cell divides quite neatly into three stages determined by the magnitude and direction of the predominating vertical motions. The stages are:

- the towering cumulus stage – characterised by an updraft throughout the cell;
- the mature stage – characterised by both updraft and downdraft, at least in the lower half of the cell (this is the stage of maximum lightning activity);
- the dissipating stage – characterised by downdrafts throughout the cell.

The towering cumulus stage

The towering cumulus stage typically has (See Figure 12.3A) updraft strength of 2000 to 4000 feet/minute, which is stronger than ordinary convection. This stage is therefore considered to be the beginning of the thunderstorms cell's life cycle when the cell is dominated by updrafts.

At this stage there is a significant concentration of rain or ice (or both) suspended within the updraft at or slightly above the cloud freezing level. Therefore, the first radar echo in an ordinary thunderstorm cell will come from near the freezing level. Lightning is seen rarely at this stage.

The mature stage

The mature stage (see Figure 12.3B) begins when precipitation starts falling from the cloud base. Meanwhile the updraft continues and often reaches its greatest strength in the upper parts of the cloud. Upon reaching the equilibrium level (refer to Chapter 8, Figure 8.6), the updraft spreads out into the characteristic anvil. Depending on the updraft speed, some overshoot of cloud tops often occurs, protruding above the anvil. At the mature stage updrafts can reach a maximum intensity of 8000 to 10 000 feet per minute.

Downdrafts associated with the precipitation arise from two main processes:

- frictional drag by precipitation particles;
- chilling of unsaturated air by evaporation of raindrops and cloud droplets.

The mature stage is the most intense period of the thunderstorm's life cycle. Up and downdrafts and turbulence are at their maximum, lightning is most frequent throughout the cell, precipitation is most intense, maximum radar reflectivity is observed and storm tops are at their highest.

Dissipating stage

The dissipating stage (See Figure 12.3C) begins when the downdraft's low-level outflow spreads out and 'undercuts' the updraft, cutting off its source of warm, moist air.

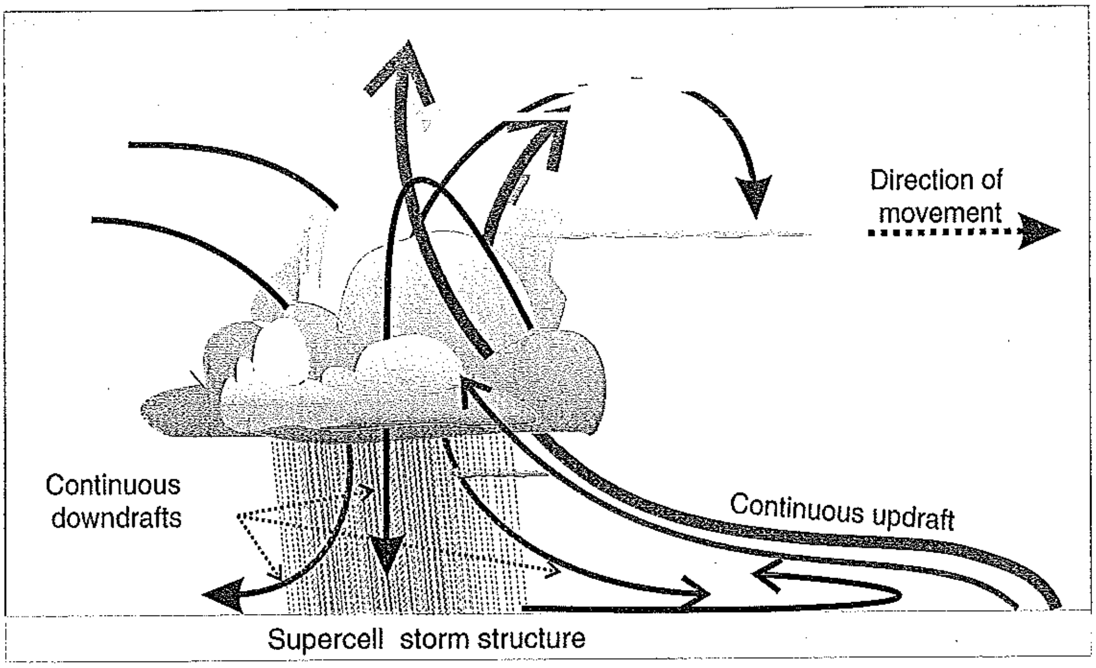


Figure 12.4
An updraft feeds into a cell from near ground level. Within the cell the updraft rises and rotates in a manner that allows downdrafts to descend away from the updraft region. Separation of up and downdrafts allows the updraft to continually feed the storm.

The dissipating stage is dominated by downdraft. Therefore, the well-defined cumuliform cloud towers that characterise the first two stages disappear and only ragged clouds remain. After the precipitation stops, the anvil aloft may be the only remnant of the storm cell. Eventually the anvil evaporates and disappears.

The cumulus stage typically lasts 10-15 minutes; the mature stage 15-30 minutes and the dissipating stage 30 minutes or so. During this time, the storm may travel many kilometers in the direction of the mid-level winds in which it is embedded.

12.4 Necessary Conditions For Thunderstorm Development

There are three necessary conditions for thunderstorms to develop. They are:

- *Low-level moisture* – sufficient water vapour in the near-surface layers to allow significant buoyancy once air from this level has reached the Level of Free Convection (LFC). The LFC is the level at which a parcel of saturated air becomes warmer and therefore more buoyant than the surrounding air and begins to rise freely.
- *Instability* – a deep layer of conditionally unstable air above the LFC which allows the parcel of saturated air to continue to rise to a considerable height, i.e. to the -20°C level and beyond.
- *A lifting mechanism* – to lift a parcel air from near the surface to its LFC. Discussed further in section 12.5.

For supercell development, the vertical wind structure must be such that the updraft and downdraft remain separated for a long period. Figure 12.4 shows the organised structure of a supercell severe thunderstorm, with separate regions of continuous up and downdrafts.

12.5 Lifting Mechanisms And Preferred Zones For Thunderstorm Development

Lift is required to initiate thunderstorm updrafts, because the atmosphere is never sufficiently unstable for deep moist convection to begin spontaneously. Lift is most often initiated by low-level air mass convergence near the surface. There are many lifting mechanisms that force convergence and induce lifting of the air. Some regions where lift can be expected are in the vicinity of:

- fronts;
- pre-frontal troughs;
- easterly troughs (an Australian feature of warmer months);
- orography;
- convergence between locally generated winds;
- convergence between synoptically and locally-generated winds;
- thunderstorm outflow.

Fronts

Air mass convergence is a feature of cold and warm fronts. Moving or stationary frontal zones have convergent zones across the frontal wind field discontinuity as illustrated in Figure 12.5.

Pre-frontal troughs

Air mass convergence occurs in the vicinity of pre-frontal troughs in southern Australia. Pre-frontal troughs frequently form ahead of cold fronts over Australia in the warmer months as depicted in Figure 12.6.

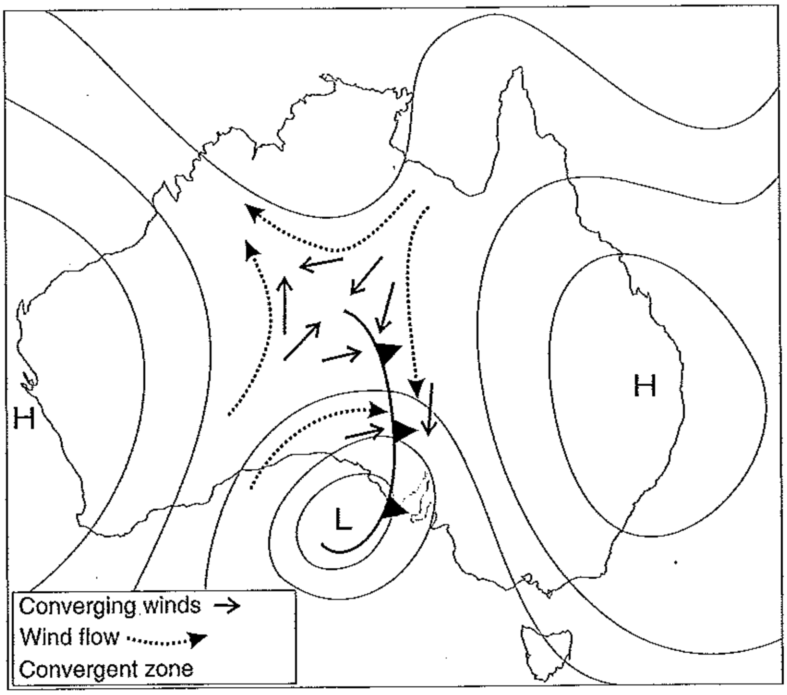


Figure 12.5

A convergent zone in the vicinity of a cold front. Note the converging northerly and southwesterly winds in the southern sector and the converging northeasterly and southeasterly winds in the northern sector. The shaded area outlines the region of maximum convergence, coincident with the most likely area for thunderstorm development.

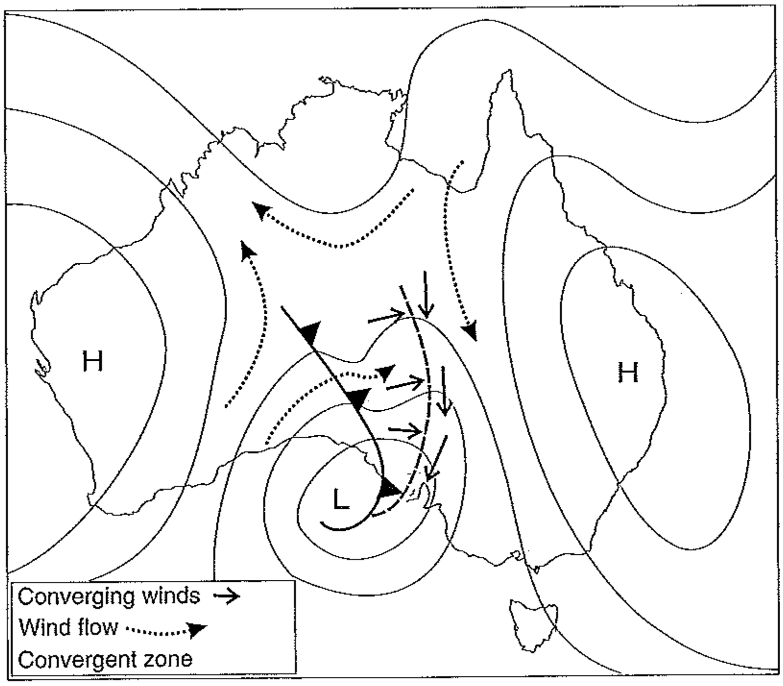


Figure 12.6

A convergent zone in the region of a pre-frontal trough. Note the converging northerly winds with the westerly winds flowing into the trough. The shaded area outlines the region of maximum convergence, coincident with the area most likely for thunderstorm development.

Easterly troughs

Convergence occurs along or ahead of a trough in the easterlies.

Troughs frequently form in easterly winds over the Australian continent, especially during the warm season. For example in Southeast Queensland, a common area for thunderstorm updraft initiation is near a small surface low at the junction of an inland trough and a coastal front, as depicted in Figure 12.7. Convergence produces strong uplift. Easterly winds from the ocean inject large quantities of moisture into the system.

It is interesting to note that easterly winds from the Pacific Ocean can, over several days, inject moisture far inland, across Queensland, New South Wales and the Northern Territory and into South Australia. If trough lines develop when the high levels of moisture are present, extensive thunderstorm systems often become established. The systems usually peak in the mid afternoon with maximum surface heating. They often collapse during the night only to re-form during the next day.

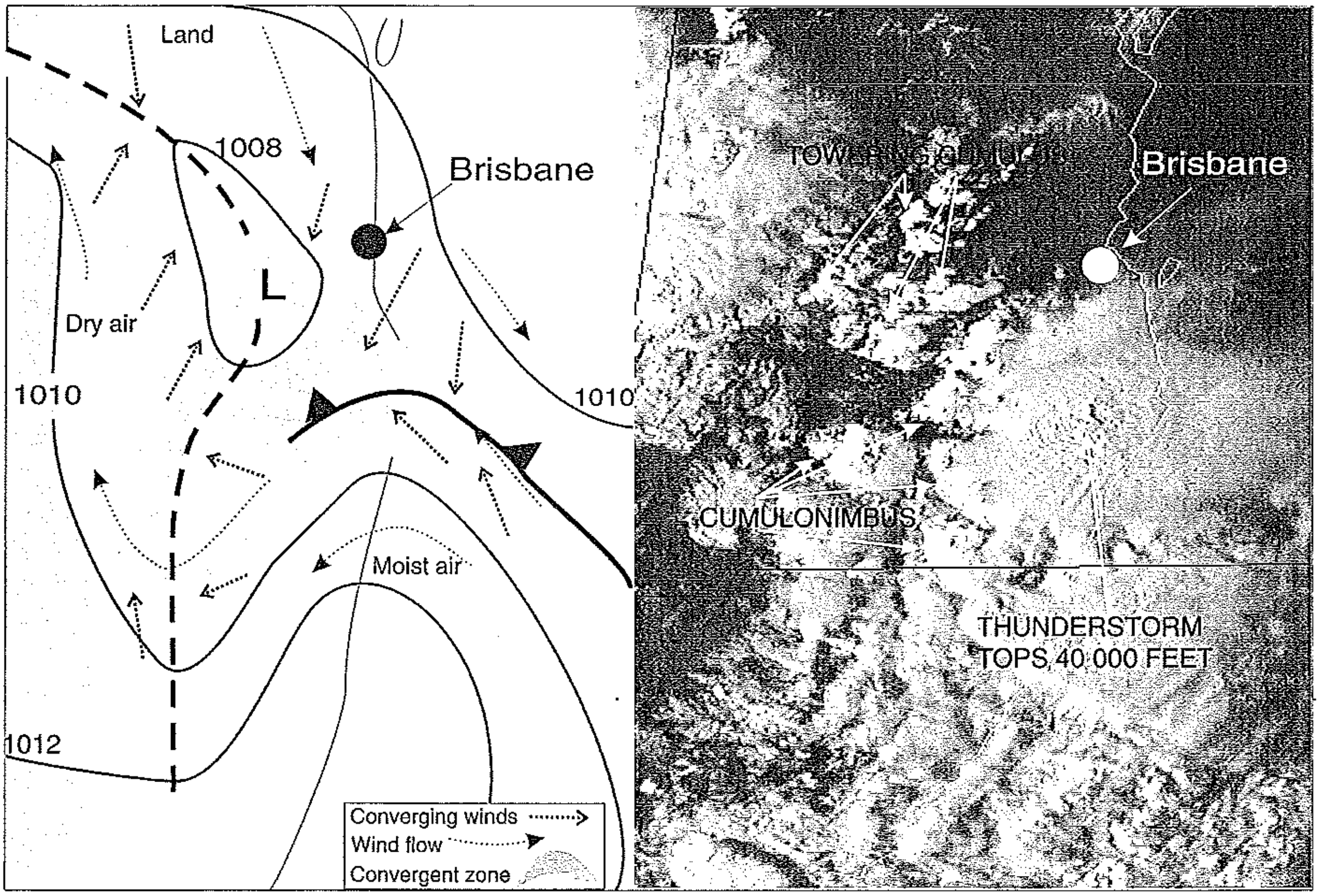


Figure 12.7

A common synoptic pattern for thunderstorm initiation in Southeast Queensland, with an accompanying image depicting thunderstorm activity. A small surface low on the inland trough combines with the coastal front to generate a convergent zone and uplift. The satellite image shows towering cumulus and cumulonimbus clouds. Of particular interest is the thunderstorm with tops to 40 000 feet. The banded structure is indicative of over-shooting tops (tops rising beyond the equilibrium level). It is also a signature of the potential for severe weather.

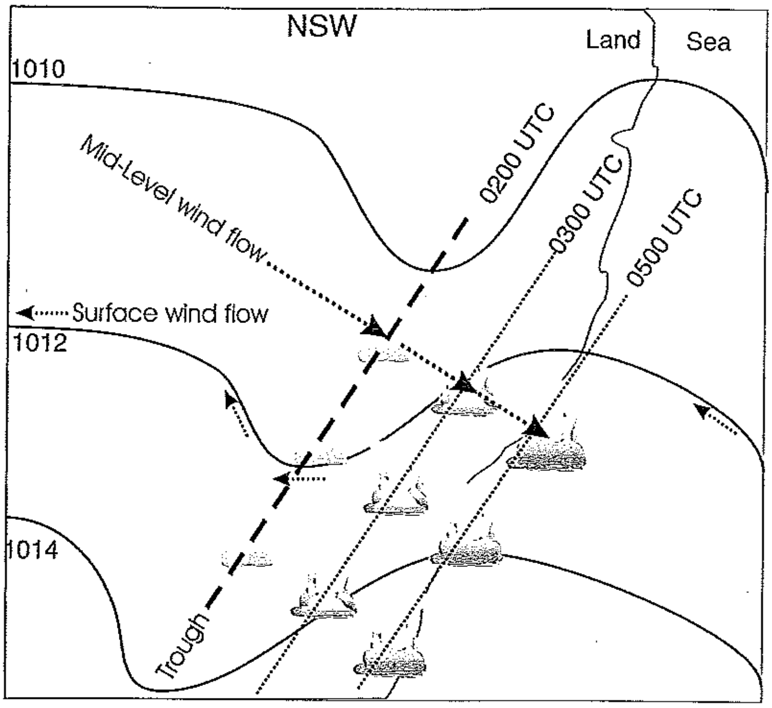


Figure 12.8
Example of the inland (easterly) trough acting as a thunderstorm lifting mechanism in NSW. The storms tend to form near the trough line and move towards the east in the steering flow (mid-level flow). Orographic-induced convergence also may play a role here.

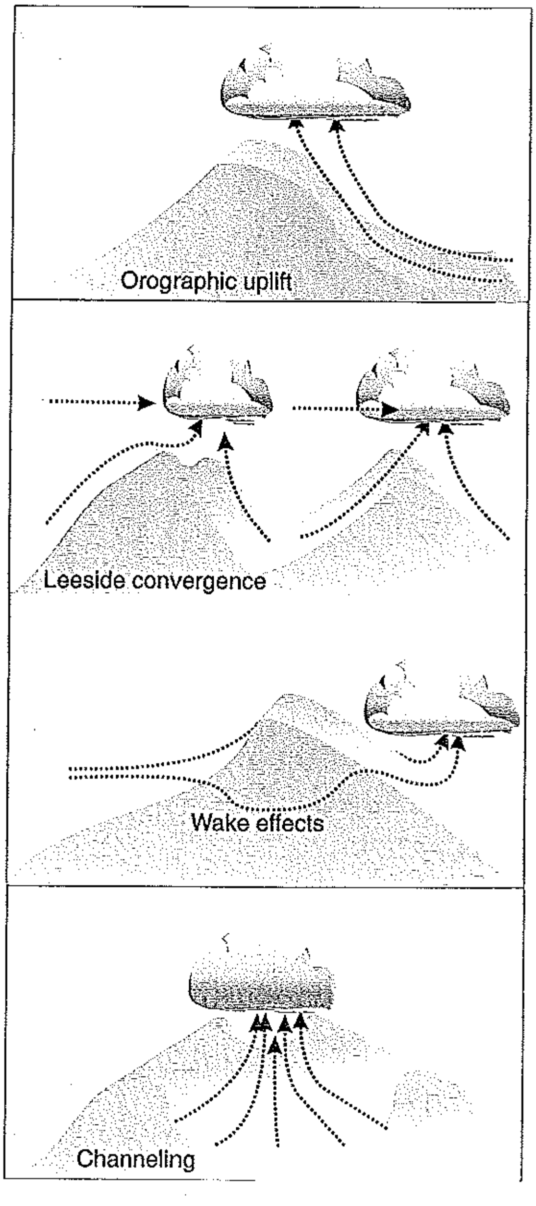


Figure 12.9
Schematic depiction of lifting mechanisms in mountainous terrain.

Orography

Thunderstorms frequently occur adjacent to topographical features due to low-level lifting. The lift is produced through local convergence of topographically forced winds. Some examples are depicted in Figure 12.9.

Convergence between locally-generated winds

Local winds generated by differential heating include sea, land breezes and lake breezes, mountain-valley winds, urban heat island winds and winds generated at a clear/overcast sky boundary, a wet/dry soil boundary or a vegetated/bare soil boundary. Examples are:

- differential heating over varying terrain leading to convergence over local hot spots;
- convergence of sea-breezes generated on opposite sides of islands or peninsulas, e.g. Cape York Peninsula and Melville Island (see the example in Figure 9.16).

Convergence between synoptically and locally-generated winds

This is exemplified by convergence between synoptic easterlies and the northwest sea-breeze over Darwin in summer, often revealing itself as a line of cumulus by midday. Many Australian coastal regions experience strong sea-breeze convergence inland from the coast during summer. Although the cool air behind the sea-breeze often suppresses convection at the coast, convergence at the leading edge acts as a lifting mechanism a little further inland. If the atmosphere is conditionally unstable and moisture sufficiently high, thunderstorms may be triggered at the sea-breeze front.

Thunderstorm outflow

Finally, thunderstorms themselves play a very significant role in new updraft initiation by generating low-level convergence along their cold air outflow boundaries. Often these outflow boundaries appear on the satellite picture as arc cloud lines consisting of cumulus clouds (Figure 12.10). Even old outflow boundaries as far as 300 km from their parent thunderstorm can generate significant low-level convergence.

Colliding outflow boundaries can produce intense low-level convergence and hence lift. Vertical speeds of 3200 feet per minute have been measured in these situations. This low-level lift is a common storm initiator, especially in the tropics. Obviously flying at low levels between or beneath storms with vertical velocities of this strength would be extremely uncomfortable and even dangerous.

The images in Figure 12.10 and Figure 12.11 are one hour apart. Within this time the gap between the two storm complexes has been filled with new convection and the clouds have moved further east.

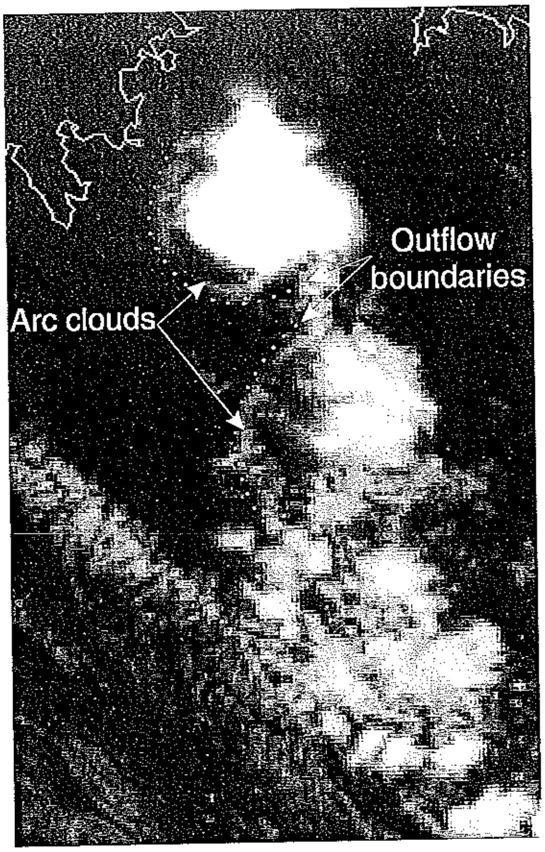


Figure 12.10
Example of two arc cloud lines generated by outflows from thunderstorm complexes. The lower arc cloud has travelled approximately 150 km from the source region. The thunderstorm clouds (cumulonimbus) have tops at -63°C corresponding to height of 45 000 feet.

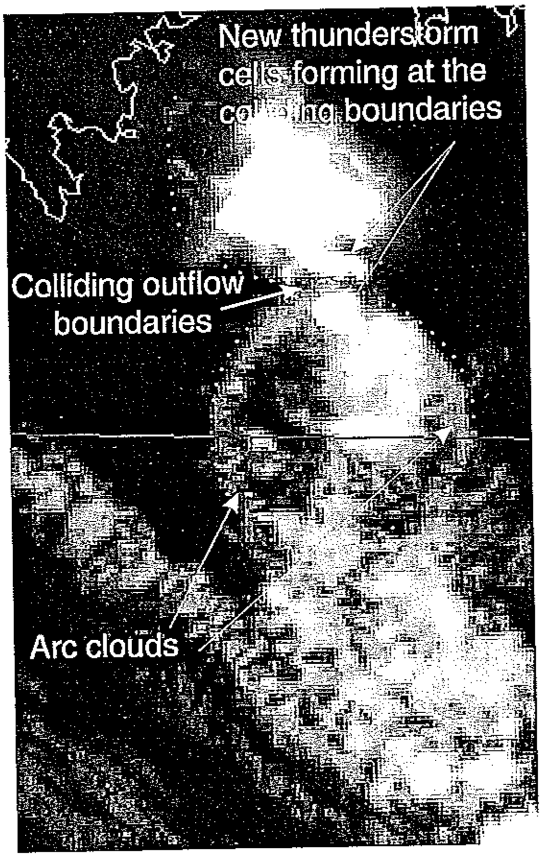


Figure 12.11
Example of outflow collision and enhanced uplift forcing new thunderstorm development. The span of the outflow from the lower complex is near 550 kilometres in diameter. The two storm complexes in this image span an area of more than 800 kilometres.

The following excerpt from the magazine Flying Australia highlights the potential danger of flying between thunderstorms.

> The narrow corridor in which I was flying was like an upside down chasm. The turbulence was extreme – it was difficult even keeping my headphones on – it was impossible to adjust the power settings – because of the jarring action of the turbulence – I remember a sense of complete helplessness – I felt that the full scale deflection of the control column had no effect – every time I sensed a clearing – it was not to be – throughout this I was hand flying the aircraft, and with great difficulty, the auto pilot didn't stand a chance in these extreme conditions.

Just prior to this experience the pilot had thought that he had been flying for long enough to believe he could handle just about any situation. But the perceived level of ability did not match the reality.

12.6 Thunderstorm Hazards

Hazardous weather conditions can be packed into very concentrated zones in and around thunderstorms. Hazards include microbursts, severe wind shear and turbulence, large hail, icing, lightning, tornadoes, heavy rain and poor visibility. Lesser known hazards can include engine water ingestion and marked variations in altimeter readings.

The capacity for thunderstorms to congregate into huge complexes over short periods of time is a danger in itself. Late morning clear skies may be filled with active thunderstorms by early afternoon.

Turbulence

"It was impossible to adjust the power settings and synchronise the propellers because of the jarring action of turbulence" *(Excerpt from Flying Australia).*

All thunderstorms are characterised by internal turbulent flows generated by up and down-draught winds, with most of them possessing the potential to produce extreme turbulence that potentially poses a significant threat to aircraft. The most likely areas in the vicinity of a thunderstorm where turbulence may be encountered are:

- updraft/downdraft boundaries within the cloud;
- the leading edge and upper surface of the gust front (where strong vertical and horizontal wind shears exist);
- funnel clouds extending from cloud base (sometimes reaching the ground as tornadoes);
- the upper parts of the updraft within the cloud (note - the airflow in the updraft near cloud base is usually quite smooth).

Pilots should monitor the movement and development of thunderstorms in order to avoid them by at least 20 nm (37 km).

Updraft winds

Updrafts tend to be strongest in the middle and upper parts of the storm, but the updraft beneath a growing cumulus may be strong enough to suck a glider or light powered aircraft into the cloud.

Updraft/downdraft Wind Shear

Wind shear between adjacent up and downdrafts within thunderstorms can generate extreme turbulence. The danger in extreme turbulence is two-fold:

- severe loadings may be imposed on the aircraft structure
- violent changes in aircraft attitude may induce stall or other conditions in which an attempted recovery may exceed the design limitations of the aircraft.

Straight line downdraft winds

As a thunderstorm goes through its life cycle, the wind field under the cloud undergoes significant changes. During the early part of storm growth, the surface winds converge beneath the cloud. However, the onset of the downdraft transforms the sub-cloud environment. When the mass of cool descending air strikes the ground, it rushes outward in all directions. The outward flowing cold air undercuts the warmer

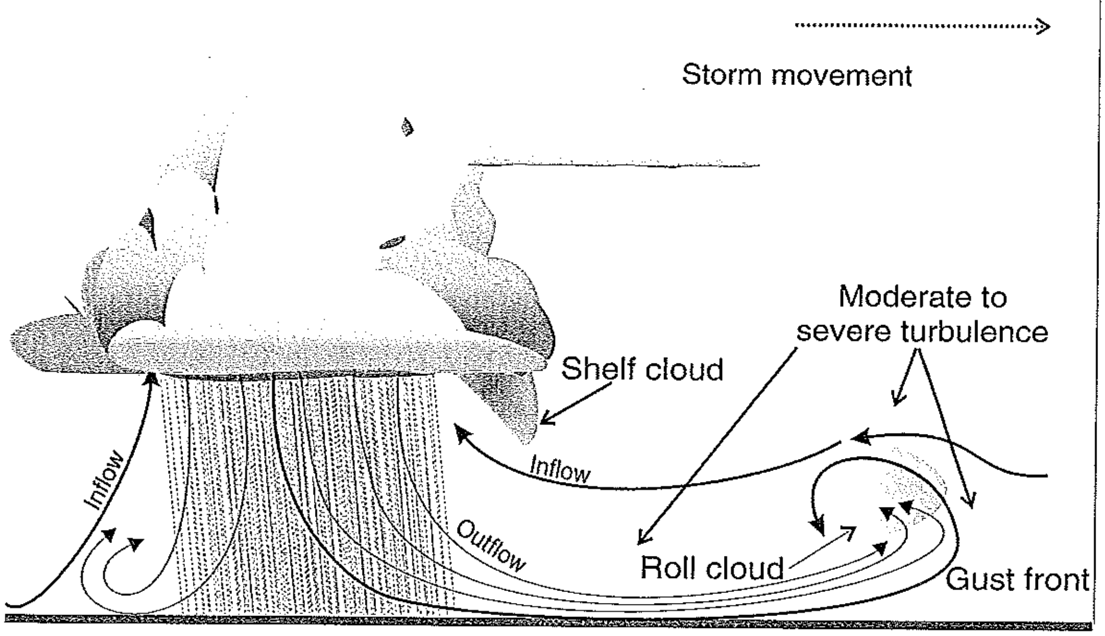


Figure 12.12
Schematic of a gust front advancing ahead of a thunderstorm, with regions of roll cloud formation and turbulence. Note that the strongest lift and most severe turbulence is at the gust front that is sometimes seen as a roll cloud. The roll cloud may be observed to be moving upwards or rotating along a horizontal axis, due to the strong vertical wind shear between the inflow (thick black lines) and the outflow (thin lines). Low cloud (shelf cloud) attached to the main base is often observed at the leading edge of a supercell.

environmental air and continues to move outward, forced by the downdraft.

The forward edge of the boundary, the gust front (Figure 12.12), is like a miniature cold front because it separates regions of air having distinctly different properties. As it spreads horizontally, it forces the warmer air to rise and can lead to the formation of new convective clouds and thunderstorms.

The strongest lift coincident with moderate to severe turbulence is at the leading edge of the gust front. At the gust front a roll cloud is sometimes observed, with strong upward motion on the leading edge, and general rotation along its horizontal axis.

Measurements of the wind gusts at the leading edge of the cold outflow occasionally exceed 100 knots.

Although the wind gusts accompanying

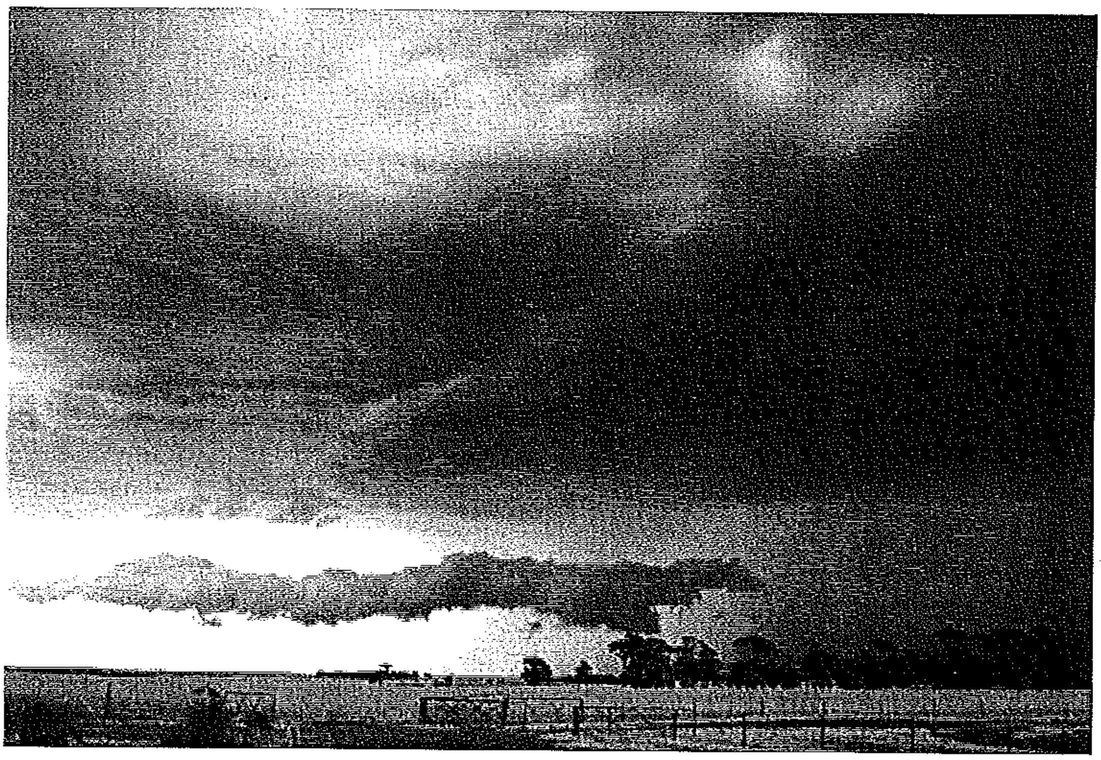


Figure 12.13
A roll cloud at the leading edge of a thunderstorm gust front (Photo: © Inflow Images).

the arrival of the cold outflow are quite pronounced at the surface, the wind speeds are usually strongest 450 feet to 1200 feet above the ground, due to frictional retardation nearer to the surface associated with surface roughness.

The initial depth of the cold outflow varies between 1800 to 4500 feet. The outflow gradually weakens and becomes shallower as it flows away from the thunderstorm.

Low-level horizontal, wedge-shaped cloud called shelf cloud (Figure 12.12) is often observed attached to the convective storm's cloud base. At times the cloud looks much like a curtain, with a hanging terraced appearance, with several layers of cloud. It can be associated with turbulence and sharp wind shifts. Up-motion can usually be detected on the forward flank of the shelf cloud while the underside appears turbulent.

Wind shear, associated with downburst and microburst

Downburst and microburst are terms used to describe small scale but particularly concentrated downdrafts that are associated with severe wind shear, as distinct from the broader gust fronts.

The term microburst describes the size of the downburst that is usually considered to have horizontal dimensions of less then four kilometres. It is important to acknowledge that microbursts are not only associated with thunderstorms. Although not as intense, microbursts can also occur under altocumulus cloud and high-based cumulus cloud.

Downburst winds differ from tornadic winds in that they originate from the cloud base and diverge when they contact the ground. Tornadic winds converge toward the cloud base. Microburst ground damage is typically in a straight line (trees are flattened all in the same general direction). Tornadic damage is usually along a narrow, well-defined path with debris often laying in disorganized patterns.

When a downburst hits the ground (Figure 12.14) it displays characteristics similar to that of a concentrated stream of water from a tap which impacts on the base of a sink, flattening and spreading rapidly outward, with a very turbulent region at the outer edges.

BE AWARE – Downbursts are a real threat to the safety of aircraft of all types. The rapid change in wind speed and/or direction poses a very real threat to aircraft during take-off and landing. Wind speeds to 146 knots have been recorded with downburst activity. The lifetime of a downburst typically lasts 5 to 15 minutes.

Figure 12.14
Schematic of downburst. A mass of cold air falling from a cloud hits the ground and spreads out.

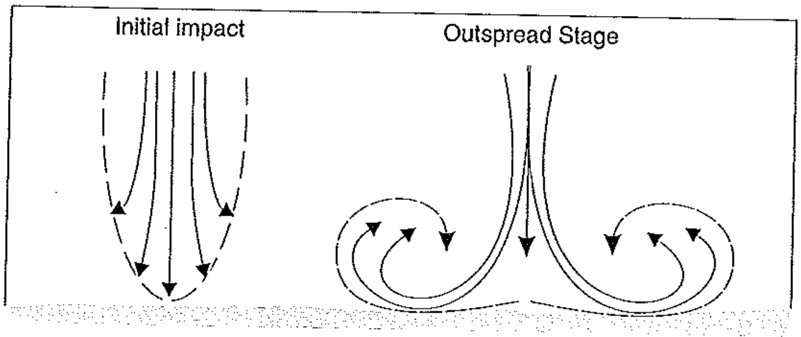
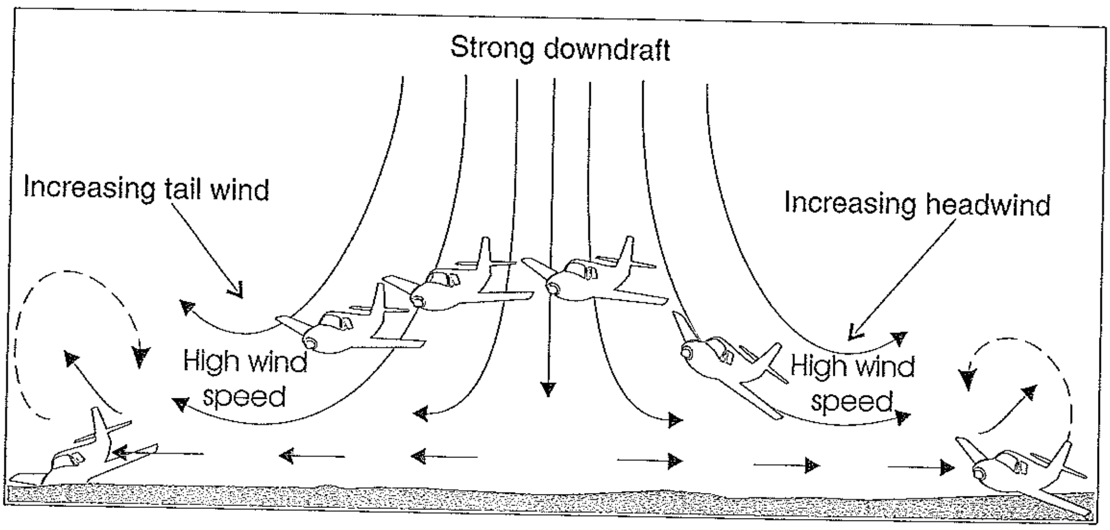


Figure 12.15
The path of an aircraft taking off into a microburst. At first the aircraft experiences a head wind, followed by a short period of decreased head wind, then a downdraft, and finally an increasing tail wind, possibly leading to disaster.



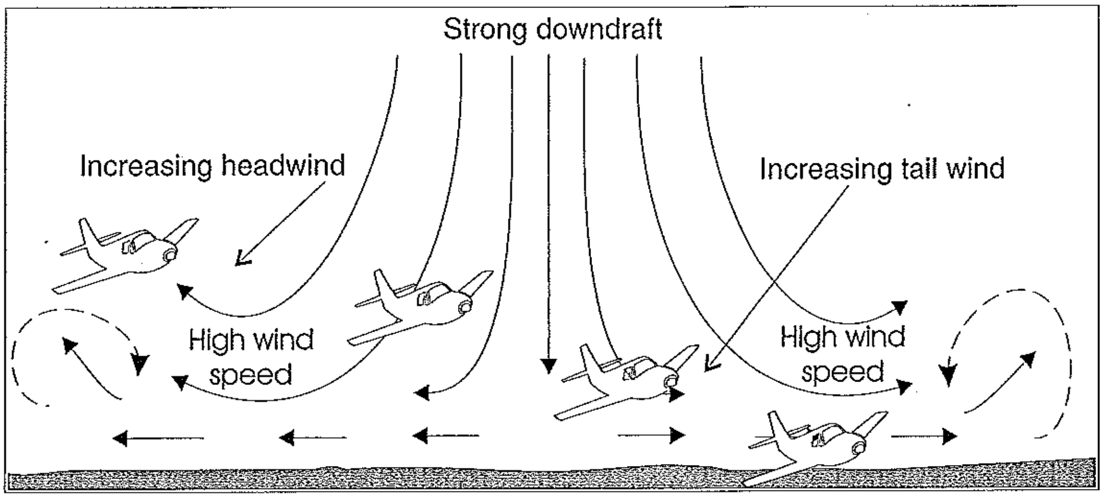


Figure 12.16
The path of an aircraft caught in a microburst while approaching to land. The aircraft beginning the descent experiences a strong headwind, then a downdraft and finally a strong tail wind.

If a downburst occurs over an airport:

- during take-off the aircraft first encounters a strong headwind that is the laterally spreading section of the downburst, then a downdraft, which is the vertically descending section of the downburst, and finally a region of strong tail wind (see Figure 12.15);
- during landing the aircraft flies into a strong head wind, then enters a region of strong downdraft before encountering a strong tail wind (see Figure 12.16).

In the United States during the 1970s and early 1980s a number of large passenger jets crashed just after take-off or just before landing. The microburst has been established as the major factor in those accidents.

The following extract from an ATSB report illustrates the dangers associated with wind shear and thunderstorm activity.

> During the approach the co-pilot requested a wind check from the aerodrome controller. The controller advised the crew that the runway 03-threshold wind was 300 degrees at 12 knots, giving a crosswind of 12 knots. The controller requested the crew to advise the spot wind at 1000 ft, and the co-pilot reported that the 1000 ft spot wind was 280 degrees at 35 knots.
>
> On short final, at approximately 500 ft above ground level, the pilot in command discontinued the approach when the aircraft experienced turbulence rendering the approach unstable.
>
> The subsequent inspection of runway 24 revealed a scrape mark on the runway approximately 490 metres from the threshold of runway 24. The scrape mark was approximately 30 metres in length and was located approximately 18 metres left of the runway centreline just outside the outer edge of the runway touchdown zone markings. Examination of the manufacturer's data for the B747-200 series showed engine number 1 to be 21.2 metres outboard from the aircraft centreline. This was consistent with position of the scrape mark on runway 24.
>
> At the time of the occurrence the environmental wind was strong, and the investigation concluded that it was likely that the downdrafts and associated surface outflows from the entrained convective activity were distorted in the direction of the prevailing airstream, and that this accounted for the gusting conditions that were present at the time of the occurrence.
>
> The flight data recorder fitted to EBS was not equipped to record the aircraft's groundspeed, and the investigation was unable to determine the actual external winds that affected it during the approach and landing. However, from the meteorological data that was available, it was probable that the roll rate encountered by EBS as it commenced the landing flare resulted from an encounter with low-level windshear. It is likely that this was produced by a

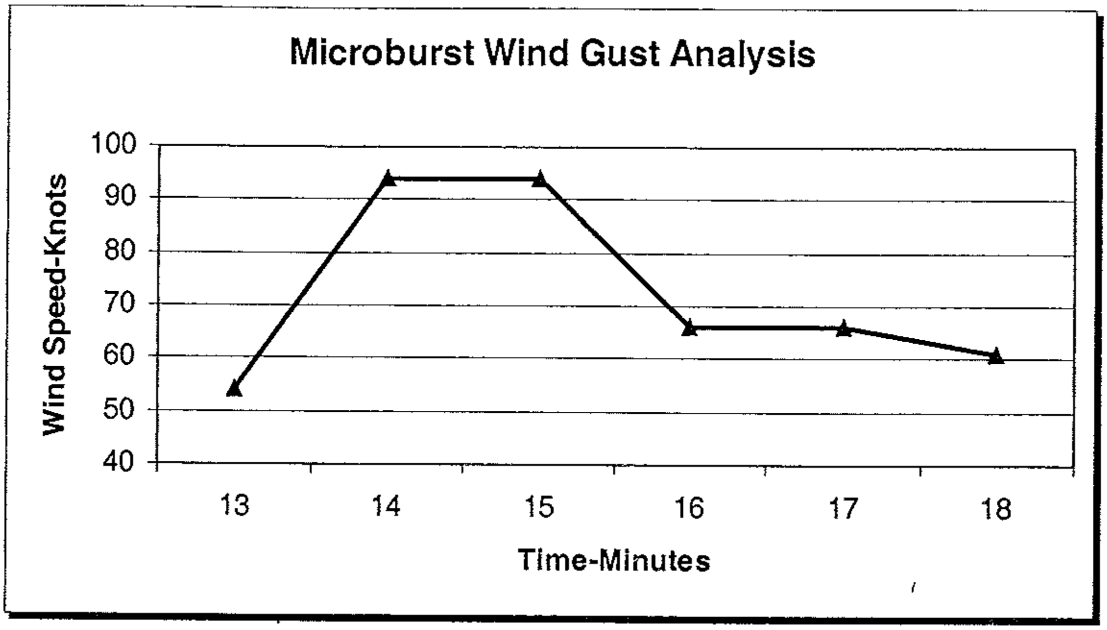


Figure 12.17
A severe thunderstorm microburst wind analysis for Richmond (Australia) for 3 December 2001. The plot is of wind gusts from SPECI reports across the life span of the microburst. The first point (at 13 minutes) and the last (at 18 minutes) are indicative of wind gusts before and after the microburst event. The microburst had a life span of about 5 minutes (between the 13 minute to 18 minutes plots). Wind gusts before and after the event were about 20 knots but for a wild 5 minute period, wind gusts varied, with gusts of 50, 94, 66 and 60 knots recorded.

downdraft from one of the convective storm cells passing through the terminal area at the time.

Although the pilot in command responded in a timely manner with appropriate control input, under the dynamic conditions that were encountered, it is unlikely there was sufficient available aileron/spoiler authority to counteract the high rate of roll that had suddenly been experienced. This resulted in the number 1 engine pod momentarily striking the ground as the aircraft touched down.

Low-level windshear may occur as a result of thunderstorms, land/sea breezes, low-level jet streams, mountain waves and frontal systems. There have been accidents and incidents associated with low-level wind shear in Australia. Pilots should be aware that it is a phenomena that may occur at any location, is difficult to predict, and can present a hazard to aircraft on approach and departure.

The analysis in Figure 12.17 is indicative of winds experienced with microburst activity and emphasises the point that aircraft should stay well clear of downbursts.

There are two types of microburst: the *dry microburst* and the *wet microburst.*

Dry micoburst

Dry microbursts develop in environments characterised by dry low-levels and moist mid-levels. As the name suggests, precipitation at the surface is either very light or does not occur at all, but virga may be evident.

The dry microburst is initiated by evaporative cooling. If the air underneath a cloud is relatively dry then rain and ice crystals falling from the cloud will quickly

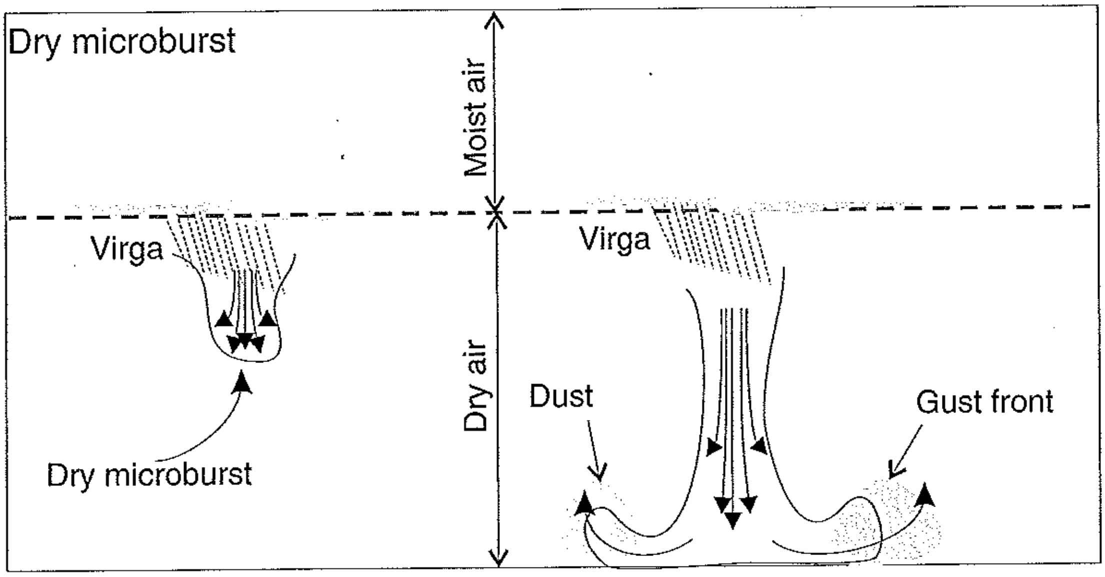


Figure 12.18
A model of the evolution of a dry microburst characterised by moist air overlying dry air.

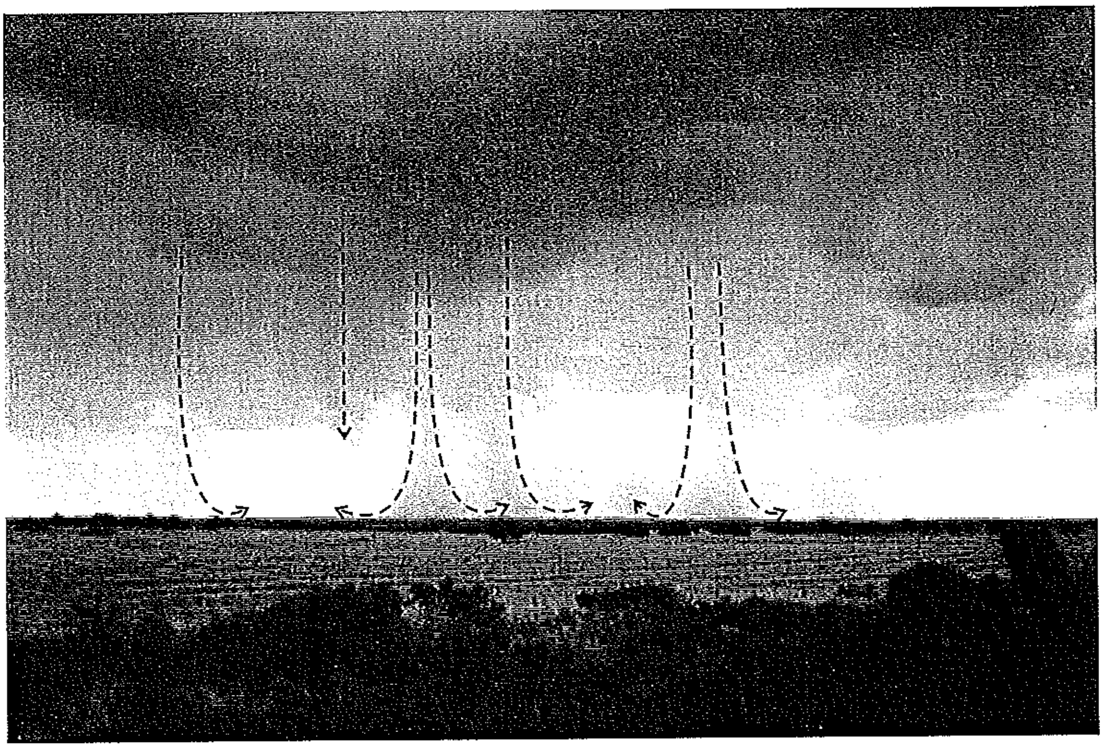


Figure 12.19
A series of dry microbursts falling from high-based cumulus cloud. Note that little precipitation is reaching the ground. The straight line arrow depicts the initiation stage of a microburst while the curved lines show the impact stage of a microburst (Photo: © Inflow Images).

evaporate and chill the air. The cooled air will be heavier than the surrounding environmental air and will accelerate downward, as depicted in Figures 12.18 and 12.19.

Dry microbursts typically impact at ground level when wind shear is weak and the air is dry and warm through the sub-cloud layer.

Dry microbursts can develop in the absence of lightning and thunder. High-based cumulus and altoculumulus have been observed to produce damaging dry microbursts.

Wet microburst

The wet microburst is accompanied by significant precipitation at the surface. Wet microbursts occur with a range of thunderstorm types.

The wet microburst develops in environments characterised by weak vertical wind shear and deep moisture capped by a dry layer as depicted in Figure 12.20. Water drops evaporating in the dry layer cool the air that then falls through the cloud. The falling air, combined with the drag of falling raindrops, produces strong downburst winds. When the downburst hits the ground it spreads out and away from the rain shaft as depicted in Figures 12.20 and 12.21.

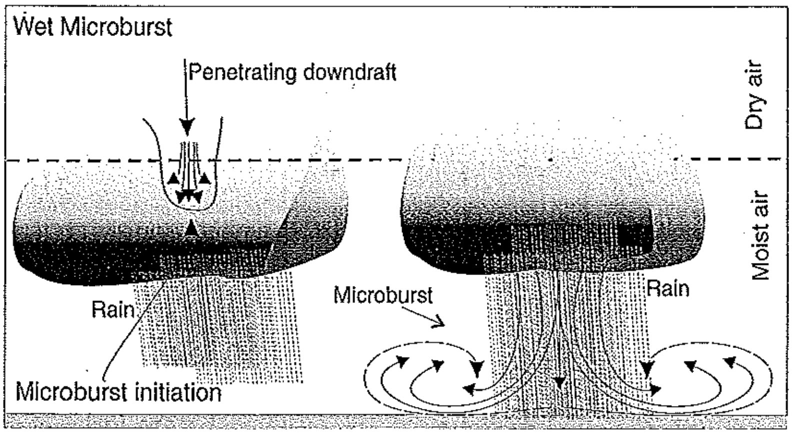


Figure 12.20
A wet microburst triggered by evaporation of cloud droplets near dry air aloft. The cooled, heavier air fuels the microburst.

Precipitation

Aircraft encountering very heavy rain, particularly during take off and landing may experience dramatically reduced performance due to the weight of water on the airframe. Another problem with heavy rain occurs with large quantities of water lying on runways as is evident from the following extracts from an ATSB report.

Extract 1

> Although the touchdown was normal the aircraft failed to stop and overran the runway end, before colliding with the perimeter fence.

Extract 2

> The aircraft overran the end of runway 21L after landing. The runway was wet from very heavy rain. The crew had flown the approach with flaps 25 selected, and had intended to select idle reverse thrust after touchdown. The aircraft encountered very heavy rain on late final approach and deviated above the glideslope. Just before touchdown, the captain instructed the first officer (the flying pilot) to go around. As thrust was being increased, the main wheels

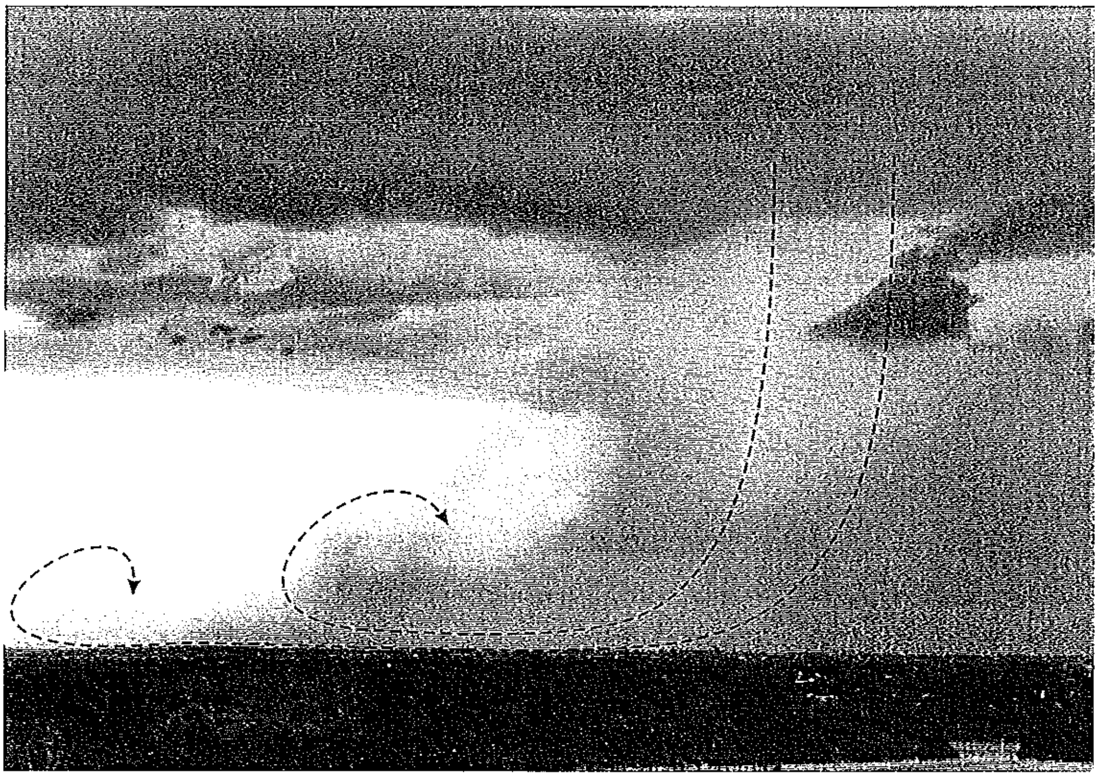


Figure 12.21
A wet microburst. Notice the lower-level cloud spreading out away from the main rain region. It is a little shallower close to the rain shaft and then appears to roll upward. Further to the left there appears to be several similar flat and upward rolling regions. (Photo: © Jimmy Deguara).

> contacted the runway. The captain then retarded the thrust levers and the crew commenced manual braking about 7 seconds later. Reverse thrust was not selected. Touchdown occurred about 1,000 m along the runway and the aircraft entered the overrun at 88 knots. Partial dynamic hydroplaning had occurred during the landing roll. This, along with the absence of reverse thrust, reducing the stopping forces available to slow the aircraft. The aircraft nose landing gear and one main landing gear separated during the overrun sequence.

In a thunderstorm with a strong updraft, water and ice particles, and even large hailstones are suspended or carried upward by the updrafts. Thus, a thunderstorm becomes an elevated storehouse of precipitation. When the amount of ice and water in storage becomes too large to be supported, or the updraft weakens, heavy precipitation begins.

The speed at which a raindrop approaches the ground depends not only on its size, but also on the strength of the downdraft. A raindrop five millimetre in diameter falls at about 1800 feet per minute in still air. In a downdraft of 2000 feet per minute, such a drop will approach the ground at a speed of 3800 feet per minute. The effect then, of a downburst on the rainfall rate, can be likened to turning a tap on and doubling the volume of water being delivered to the ground. Similarly if there are many large drops in a strong thunderstorm downdraft, large quantities of water will accumulate quickly at the surface and possibly flood runways.

The most intense rain often occurs within a few minutes of the first rain reaching the ground and can remain heavy for a period of five to fifteen minutes, before decreasing slowly. Rainfall rate depends on the position of the storm relative to the observer on the ground, and on its movement.

The rainfall pattern in a thunderstorm reflects the stages of development and location of the constituent cells. At a fixed point on the ground, the duration of the rain depends on several factors. Precipitation will occur for long periods when thunderstorms:

- are slow-moving;
- are large, or
- form in a line so that several cells move over the same area.

Tornadoes

A tornado is a rapidly rotating column of air extending from the ground to the base of a large cumulus or cumulonimbus cloud. It is usually visible as a funnel cloud, which may or may not reach the ground. It is capable of producing very destructive winds on the ground. If the rotating column does not reach the ground the phenomenon is not a tornado and is classified as a funnel cloud only. However it is still a hazard to aircraft.

Tornadoes are the most violent of atmospheric phenomena and the most destructive.

The strongest tornadoes develop in association with supercell thunderstorms. If the environmental wind shear is suitable, the strong updrafts within these storms occasionally take on a rotation, which can intensify into a tornado. Tornadoes can also occur with individual non-supercell thunderstorms and with squall line thunderstorms, but these are usually weaker. An aircraft entering a tornado is almost certain to suffer structural damage.

> While en-route, 35 minutes into the flight, the bi-plane crashed near Santa Clara. The plane was seen spinning out of control before it hit the ground. A strong gust of wind, possibly a small tornado, tore off the top part of the left wing (http://www.planecrashinfo.com/)

Hail

While hail posses a serious threat to aircraft flying within a thunderstorm, hail may also be met outside the cumulonimbus cloud under the cirrus anvil and obviously beneath the storm.

Aircraft on the ground and in flight can sustain severe damage from the impact of hail as testified in the following aircraft accident report.

> The aircraft sustained a broken windshield and loss of power to both engines after penetrating a thunderstorm and encountering hail. The plane crash landed on a highway and exploded in flames due to total and unique loss of

> thrust from both engines while the aircraft was penetrating an area of severe thunderstorms with heavy precipitation and hail (http://www.planecrashinfo.com/).

Hail is primarily a phenomenon of mid latitudes. It is rare in polar regions because the air is too cold to contain sufficient moisture, and is seldom unstable enough to generate strong updrafts. In the tropics, hail is rare because of the high freezing level. Large hail is virtually unknown in the tropics because updrafts within tropical storms are seldom strong enough to suspend ice particles long enough for them to grow into large hailstones. Large hailstones grow inside intense thunderstorms that have updrafts strong enough to hold hailstones aloft in the hail-growing regions of the thunderstorm sufficiently long for them to grow large.

Although the region where hailstones grow is at a temperature below freezing, most of the cloud is in the form of supercooled liquid water rather than ice. A supercooled drop will freeze if it comes into contact with freezing nuclei or collides with an ice particle. Thus a frozen drop of water or a snow crystal can initiate the development of a hailstone.

Hailstones grow by sweeping up both supercooled droplets and the occasional ice particle. When a supercooled drop strikes an ice surface, two things happen: it spreads out on the surface and it freezes. If it freezes quickly, it will not have time to spread very much, and will thus remain a rounded lump of ice on the surface of the parent hailstone. If it freezes slowly, it will have time to spread as a thin coating. There are many variations between these two, and therefore many variations in the shape of hailstones.

Icing

Updrafts in a thunderstorm support liquid water in the form of large supercooled droplets. Supercooled water may freeze on impact with an aircraft body and cause engine air intake problems. It may also block external instrument sensors such as pitot tubes. The abundance of large supercooled water droplets in thunderstorm cloud between 0°C and -20°C makes for ideal conditions for severe icing to occur. Icing affects are discussed in detail in Chapter 11.

Low cloud and reduced visibility

Generally visibility is near zero within a thunderstorm cloud. Below the thunderstorm, visibility can be significantly reduced in precipitation, dust and lower cloud. The hazards are increased when reduced visibility is associated with wind shear turbulence, hail and lightning.

Lightning

Lightning is a transient, high-current electrical discharge caused by electric charge separation. This occurs both within the thunderstorm cloud and between the cloud and the ground. If charge separation becomes sufficiently large, the potential difference is discharged by a lightning stroke. This can be either within the cloud, or between the cloud and ground.

Well over half of all discharges occur within the clouds. Cloud-to-ground lightning is less frequent than intra-cloud, but with severe thunderstorms can nevertheless be very frequent. Ground strokes are the primary hazards to people or objects on the ground. Storm clouds of modest size produce a few flashes per minute while severe thunderstorms can produce hundreds of strokes per minute.

Lightning can cause both direct and indirect damage to aircraft. Direct effects include puncturing of the fuselage, burning, melting or distorting aircraft metallic and non-metallic parts. Indirect effects include temporary or permanent damage to avionics equipment. The worst scenario would be a lightning strike causing a fire in the fuel tanks. Nearby lightning strikes may temporarily blind the pilot making both visual and instrument flying difficult. The following extract from an ATSB report highlight the danger of lightning to aircraft operations.

> A subsequent inspection revealed the aircraft had sustained a lightning strike on the nose. The nose cone bonding

strip had been destroyed and the resulting heat damage had ruptured the nose cone structure. The current had taken multiple exit paths through out the aircraft, rendering most electrical services inoperative, before exiting at various points on the tail surfaces.

Air pressure changes
Pressure changes associated with a thunderstorm downdraft are usually very rapid. With the approach of the storm the pressure often falls steadily, before rising rapidly with the onset of the gust front and arrival of the cold downdraft and accompanying heavy precipitation. The pressure then falls back to normal as the storm moves away. This cycle of pressure change may occur over a time span of 10 to 15 minutes. If the pilot does not have a corrected altimeter setting, the altimeter may be more than 100 feet in error as is indicated in Figure 12.22.

Engine water ingestion
Turbine engines have a limit on the amount of water they can ingest. Severe thunderstorms may contain areas of high water concentration, held aloft by strong updrafts, which could result in flameout and/or structural failure of engines. Avoidance of thunderstorms is the only safe measure to be effective in preventing engine damage or flameout as attested by the following extracts from safety reports.

Extract 1
After penetrating a thunderstorm massive amounts of water caused both engines to lose power. Although the engines were restarted the crew could not recover and crashed into a field. The crash was due to engine failure due to massive ingestion of water into both engines, crew error and an unwise decision to enter an area of thunderstorms (http://www.planecrashinfo.com/).

Extract 2
The aircraft suffered a flame-out of both engines in torrential rains while on approach to Yogyakarta. The crew made an emergency landing in the Bengawan Solo River, in shallow water. The plane circled several times before diving in a steep course towards the river. The plane's left wing struck a river bank before it plunged into the water (http://www.planecrashinfo.com/).

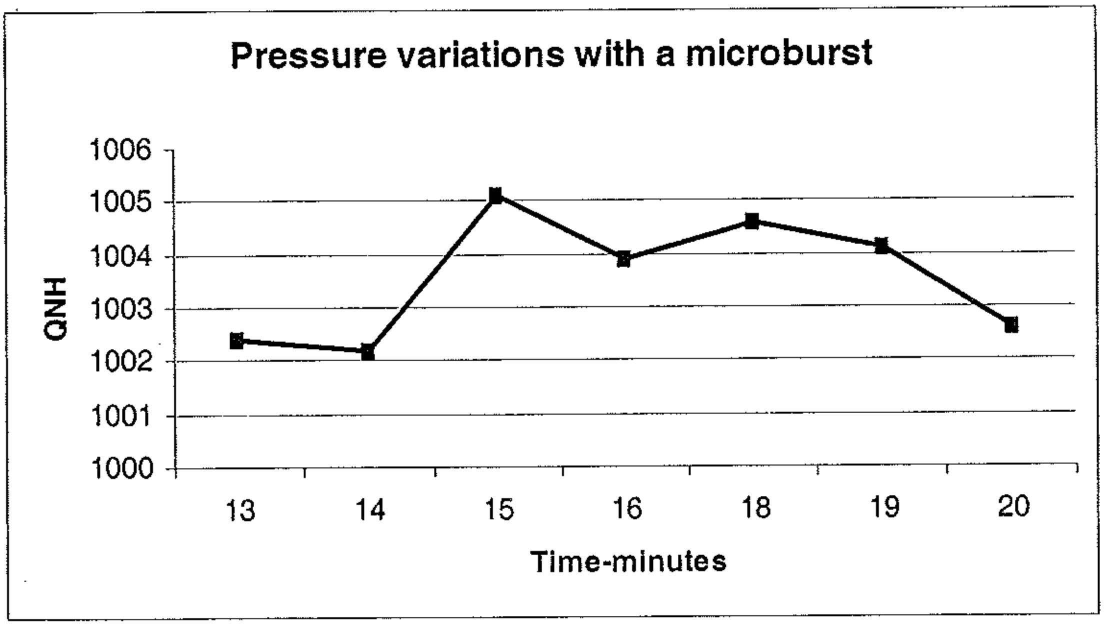


Figure 12.22
Pressure variations with the passage of a thunderstorm at Richmond on 3 December 2001. From a pre-storm QNH of near 1002 hPa, a rapid rise in pressure of three hPa occurred coincident with the maximum wind gust. The three hPa change is equivalent to an altitude change of approximately 90 feet (Chapter 5).

VISIBILITY

Aircraft operations can be severely restricted by poor visibility. For the Visual Flight Rated (VFR) pilot it is not only the specified visibility in forecasts that is of interest, it is also the air to air and air to ground visibility that is of utmost importance to safe flight. Many accidents have occurred when VFR pilots have continued flight into weather below Visual Meteorological Conditions (VMC).

In any one situation the perceived visibility can vary greatly depending on the observers point of view and the prevailing weather conditions.

13.1 Meteorological Visibility

Visibility reported in aerodrome weather reports and specified in forecasts refers to ground-level observations and forecasts of the greatest horizontal distance at which a dark object can be seen and recognised.

Visibility is intended as a measure of atmospheric transparency. It does not depend on the general level of illumination, so that night-time estimates will not vary from daytime estimates under the same meteorological conditions.

The fact that meteorological visibility is assessed at eye level by an observer on the ground is worth emphasising. An air traffic controller in the tower 100 feet or more (Brisbane is 230 feet) above ground level and the pilot on 'finals' will have a very different view. For example, in shallow mist or fog patches, the ground-level visibility may be significantly less than that from the tower.

In summary, the ground-level visibility is the visibility used in aerodrome weather reports and forecasts. It is a human assessment and is intended as a measure of atmospheric transparency in a horizontal plane.

NOTE: Meteorological visibility should not be confused with the Meteorological Visual Range (MVR) which is measured by an instrument called a visiometer which, in Australia is installed on some automatic weather stations. It is a laser instrument that measures the translucency of the air across a very short base line of about half a metre. In Australia this figure is included in the remarks section of the Automatic Weather Report (AWR) and, whilst providing useful information, should be used with care because of the very small sample of air it measures.

13.2 Runway Visual Range (RVR)

RVR is the maximum distance in the direction of take-off or landings at which the runway can be seen from a position corresponding to the average eye-level of pilots at touch-down. RVR is instrumentally derived and hence only used at those airports suitably equipped.

Values of RVR are included in ATIS (Air Traffic Information Service) reports in critical visibility conditions when an accurate assessment of the pilot's view on 'finals' is required to assist a safe landing.

13.3 In-Flight Visibility

In-flight visibility changes as the angle of view varies. For example when over-flying an aerodrome, the runway complex may be clearly visible through fog or mist but as slant angle decreases the runway may become obscured. Figure 13.1 depicts

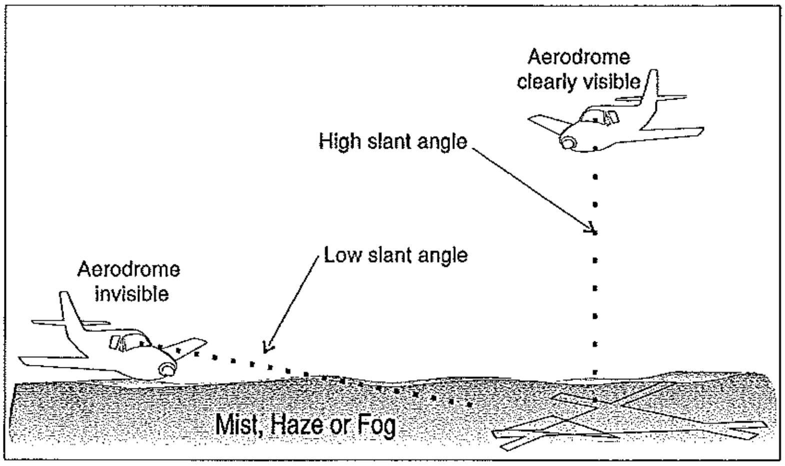


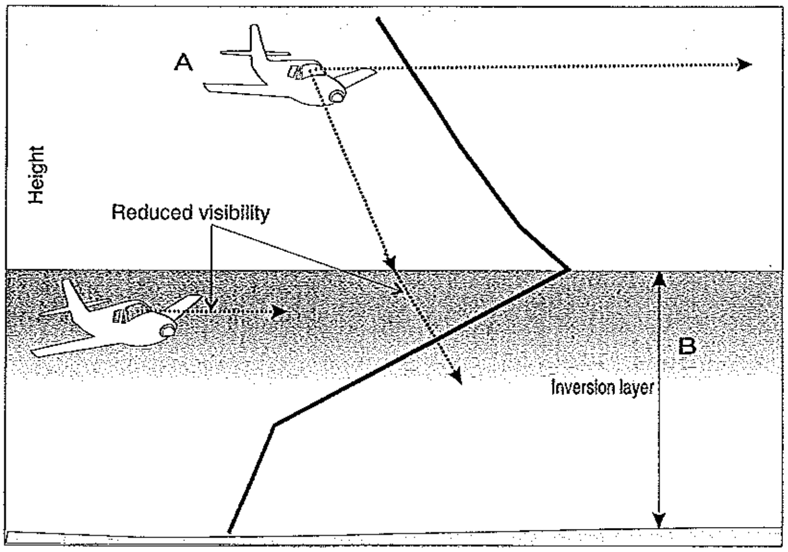
Figure 13.1
Variations of visibility due to changing viewpoints.

how high slant angles determine whether a pilot sees through less fog or mist than would be the case with low slant angles.

On other occasions a layer of cloud may reduce air-to-ground visibility while the horizontal visibility on the airfield is good.

Air-to-air visibility may be reduced by cloud, precipitation, dust, smoke, and haze. For instance, pollutants may be trapped under an inversion and reduce visibility. Flying above the inversion, at A in Figure 13.2, will ensure good forward visibility while flying within the inversion at B, will drastically reduce forward vision. A pilot at A may not be able to see the ground.

Figure 13.2
Pollutants trapped under inversion layer will reduce visibility.



13.4 Cloud Visibility

"On average, VFR pilots who enter cloud, takes just 120 seconds to lose control and begin an uncontrolled spiral dive." A quote from an aviation Weather-Wise Seminar (run by CASA), highlights the requirement that VFR pilots do not enter cloud.

Visibility within clouds may vary from less than 10 m to over 1000 m. In high cirrus visibility is generally greater than 1000 m while in middle-level clouds such as altostratus visibility ranges from about 1000 m down to 20 m. Visibility in low clouds is generally less then 30 m and may fall below 10 m in cumulonimbus and nimbostratus.

The following ATSB report clearly indicates continued flight into non-visual meteorological conditions can lead to disaster.

> Witnesses on a property 9 km west-north-west of Oberon reported hearing an aircraft overhead. They could not see the aircraft because of fog and mist but heard it circle their house twice. The engine noise increased followed by the distinct sound of an impact. They subsequently found the wreckage of an aircraft approximately 250 m west of the house. The occupants of the aircraft were fatally injured.
>
> The pilot obtained the correct weather forecasts for the flight. The investigation found no record of the pilot having updated his weather information during the flight. Consequently, although he expected a gradual deterioration of the weather he would not have had any warning of the more rapid deterioration, and greater severity of conditions.
>
> It is likely the pilot only realised that the weather was significantly different from the forecast when he was tracking across the higher terrain south-east of Oberon. Due to his lack of exposure to similar weather, it is possible he delayed making a decision to divert until too late. Having flown

into those conditions the pilot then found himself trapped between the ridges and the cloud base, unable to continue or turn back. His instrument flight skills would have been inadequate to attempt flight in cloud under those conditions. When the aircraft entered cloud the pilot was no longer able to rely on external visual references and probably became spatially disorientated. The aircraft subsequently entered a left turn, descended rapidly and collided with the ground. The accident was consistent with loss of control following flight in instrument meteorological conditions by a non-instrument rated pilot.

The significant factors:

- Weather conditions deteriorated more rapidly and more severely than was initially forecast in the weather reports obtained by the pilot.
- The pilot was unaware of amended weather information that accurately forecast the deterioration in weather conditions.
- The pilot continued flight into non-visual meteorological conditions.

13.5 Precipitation Visibility

Visibility in rain will depend on the drop size and the rate of rainfall. Therefore reductions in visibility will be greatest in very heavy rain (large droplets) and in drizzle (many small droplets). Heavy rain is also often associated with low cloud below the main base, which reduces visibility even further.

Some guidelines to visibility in precipitation are listed below. These figures are approximate, as visibility will vary greatly dependent on drop size, rate of fall, total moisture content of the prevailing atmosphere and the influence of the prevailing visibility. However the figures are of interest because they emphasise the fact that visibility in any form of precipitation can be reduced to well below safe operating conditions for VFR pilots:

• drizzle	400 – 3000 m;
• light rain	greater than 10 km;
• moderate rain	5 – 10 km;
• heavy rain	greater than 1000 m;
• heavy rain in tropical regions	50 – 500 m;
• moderate snow	400 – 1000 m;
• heavy snow	less than 400 m.

13.6 Fog

Fog is the most frequent cause of low visibility at airports. As such, it is one of the most important hazards to aviation. Widespread fog may obscure ground features so that visual en route navigation is impaired, but the major problem is its effect on landing and take-off.

Fog is defined as a concentrated suspension of very small water droplets causing horizontal ground level visibility below 1000 metres. In extremely cold climates the suspension will be ice crystals and the fog is called ice fog. Fog is actually a cloud occurring at ground level.

Fog forms in the same basic ways as cloud. Either:

- a moist air mass is cooled beyond its saturation point and condensation occurs; or
- extra moisture is added to make the air saturated at that temperature.

Most fogs are initiated when moist air is cooled by contact with an underlying cold surface, whereas clouds form as a result of moist air being cooled by lifting. In addition, some turbulent mixing of air must occur to transfer the cooled air to higher levels before fog will form to any depth.

Radiation fog

Radiation fog forms when moist air is cooled below its dew-point by contact with a cold land surface that is losing heat by radiation. The ideal conditions are:

- high relative humidity at low levels so that little cooling is required for saturation;
- cloudless, or near cloudless skies to allow large heat loss at the surface;
- light winds to promote cooling through a few hundred feet of the surface (a calm wind tends to restrict the fog to low-lying pockets).

The mixture of ingredients is often critical. Small particulate matter assists the process by providing condensation nuclei, so a fog that would not form in open countryside may form under the same circumstances near a city where small pollution particles provide the necessary nuclei. If the wind is dead calm, the cooling may take place through a depth of a few centimetres and a heavy dew is the only result. The small amount of turbulence caused by the sun's first warming rays may tip the delicate balance and change fine and clear conditions into an all-enveloping shroud.

Because cold air sinks into valleys (katabatic effect), these are preferred areas for radiation fogs, especially if a stream or river adds moisture to the air. From the air, fog can be seen like a smooth carpet snaking through the valleys while the surrounding hill tops are clear (see Figure 13.3).

Anticyclones provide the most favourable weather situations for radiation fog, particularly if the preceding situation has brought a moist air mass to the area. Moisture in the ground can also contribute, so a clear, calm night after a period of rain is a particularly favourable situation.

The depth of radiation fog varies from a few feet to over 1000 feet. As an example, a typical thick radiation fog at Canberra is 700 to 1000 feet in depth.

Radiation fog usually disperses a few hours after sunrise. An exception occurs when the fog is very thick or when middle cloud has moved over the fog and effectively blocks the heating effect of the sun.

Advection fog

Advection fog like radiation fog primarily forms by cooling from below. The difference is that the moist air flows over a cold surface.

Figure 13.3
Fog reducing visibility and obscuring lower ground.

Moist air may flow from a relatively warm sea to a cold land mass to form advection fog. A radiation cooling process over the land may well assist in the formation and maintenance of this fog, but it is still usually called an advection fog.

Another example of advection fog is moist air flowing from warm seas to relatively cold seas. This occurs most frequently when moist air streams move poleward over colder ocean waters. The fog resulting from this advection process is called sea fog. Sea fog is often widespread and persistent even in moderate strength winds. It can be a real problem to aircraft operations from a ship or to land-based aircraft engaged in maritime search and rescue or reconnaissance operations. Sea fog may drift inland over coastal aerodromes in a light on-shore wind stream.

Radiation/advected fog

Often it is difficult to distinguish between processes that result in fog enveloping an area. Frequently, fog initiated by radiation is transported (advected), by locally generated winds that are often at a peak at sunrise. Sometimes radiation, advection and upslope processes, along with local turbulent mixing of low-level air to saturation, combine to produce fog. It is this complexity that makes the forecasting of the onset and cessation of fog, at any point, quite a challenge.

Other types of fog are less common but worth noting.

Steam fog

Steam fog forms when a cold moist air mass flows over a much warmer water body. The evaporation of water from the warm water surface causes the air above the surface to become saturated. Because the surface is warmer, convection currents give the steaming appearance.

Frontal fog

Frontal fog occurs at the boundary of two air masses rather than within a single air mass as in the case of the previously discussed types. It occurs as cloud reaching or descending to the surface at the frontal edge, or forms in precipitation when the air becomes saturated. Such fogs usually form rapidly and are very extensive. The danger of such fogs to aviation is that, unlike radiation fog where the visibility above the fog is good, a frontal fog will be associated with generally poor weather such as dense cloud and precipitation. Fortunately, such fogs are not common.

Sea fog

Sea fogs are usually advection fogs. They are rare in the Australian region but when they do occur they are often widespread and persistent even in moderate strength winds. They can occur at any time of the year. Sea fog has been known to persist for several days around the Australian coastline. The main dangers to aviation presented by sea fog, are when it drifts inland over coastal aerodromes during daytime, usually with a sea breeze, or obscures the sea surface for seaplane operations.

Upslope fog

Upslope fog is formed when moist air forced up a terrain slope cools to saturation. The process is similar to terrain-induced cloud in that cooling is due to forced lifting of moist air by terrain.

Mist

Mist obscures the visibility between 1000 and 5000 metres.

Fog and low-stratus cloud

Fog frequently lifts from the surface to form low-stratus cloud. From the VFR pilot's viewpoint, low-stratus cloud can pose as many problems as fog particularly when very low to the ground.

The only real distinction between stratus and fog is the height at which it occurs. Upslope fog would appear as stratus to an observer beneath.

Stratus cloud often occurs at frontal surfaces and in precipitation, although in these cases it is sometimes patchy rather than a continuous deck. On some occasions low-stratus cloud and fog occur together. For example, a fog layer may be markedly thicker at the top. From the ground this would appear as fog or mist topped by a layer of low-stratus cloud.

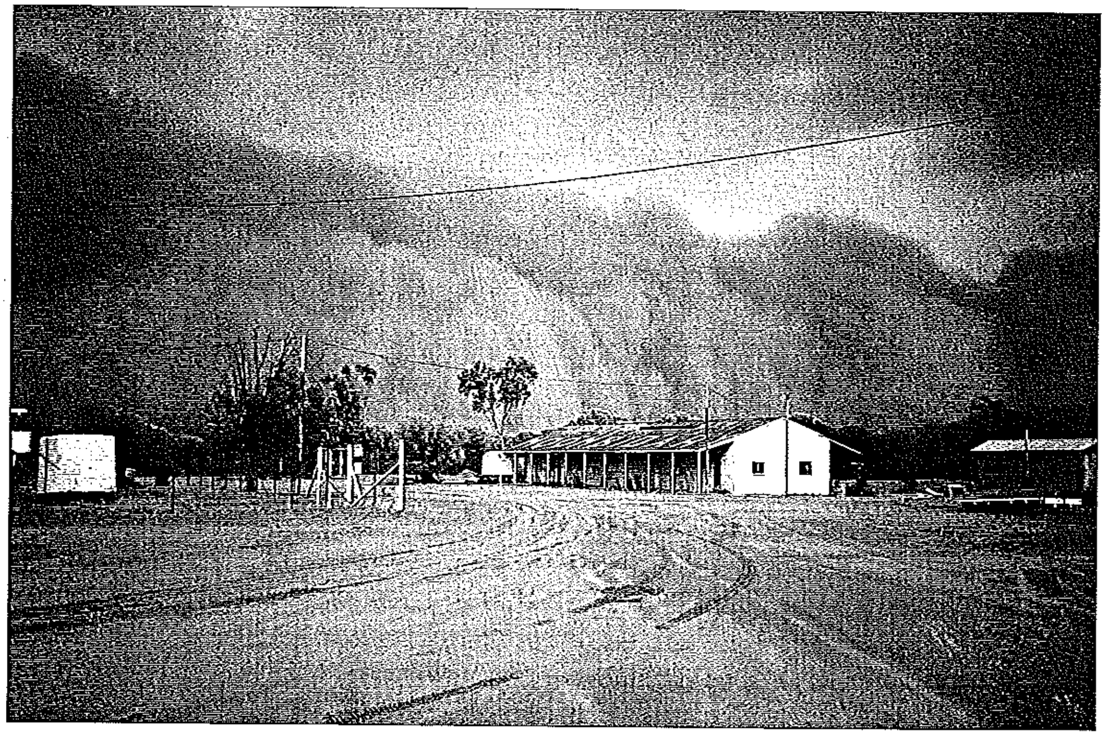


Figure 13.4
Thick dust raised to thousands of feet above the surface by strong winds over central Australia.
Photo:©Helen Clifford

13.7 Locally Raised Dust And Dust Storms

Dust storms such as those pictured in Figures 13.4 and 13.5 can cause major disruptions to flight in dry inland areas of Australia. Occasionally dust becomes a problem well away from the source region. This can occur when strong winds in conjunction with an unstable atmosphere lift and transport dust many hundreds of kilometres across Australia. At other times dust raised locally from freshly ploughed paddocks restricts visibility over contained areas. The locally raised dust has been known to severely restrict visibility at airports in Australia.

Very strong, gusty winds combined with instability will generate dust storms, defined

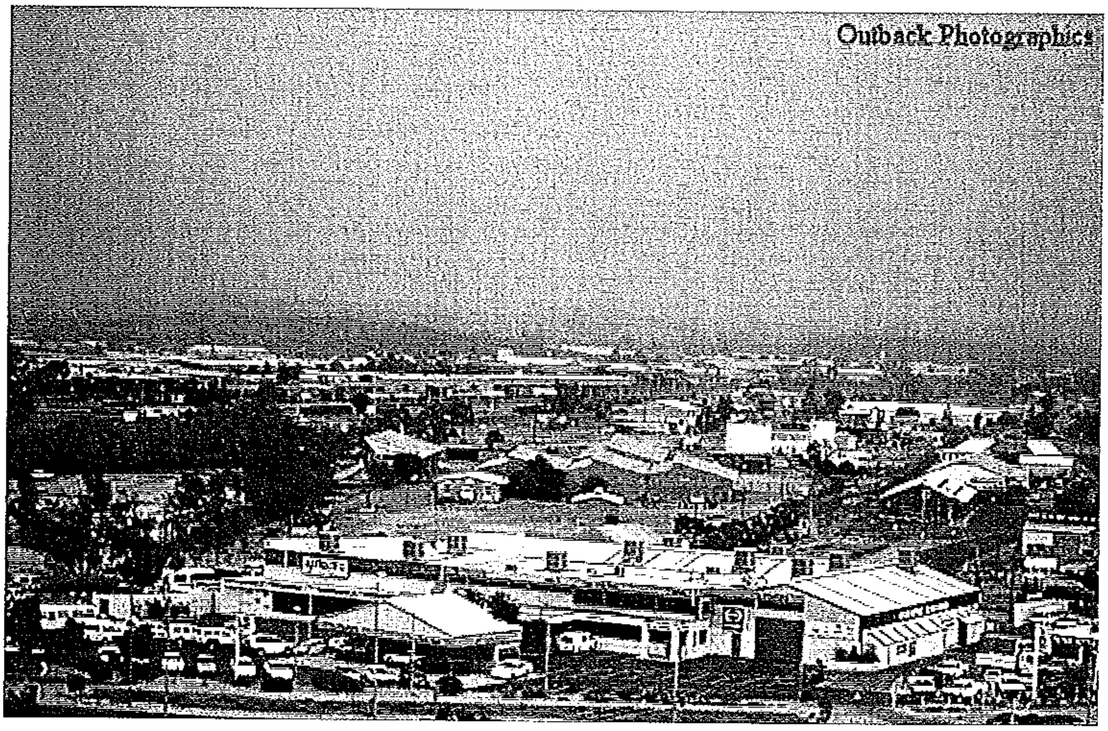


Figure 13.5
Extensive dust blanketing Alice Springs.
Photo©Steve Strike Outback Photographics

as blowing dust with prevailing visibility less than 1000 metres. A severe dust storm will reduce visibility below 200 metres. Such storms can be both widespread and deep. The depth depends on the height to which the atmosphere is markedly unstable, but is commonly well over 10 000 feet. An upper, dense pall of dust may cover areas remote but downwind of the storm even though surface visibility is reasonably good.

Aircraft with marked ceiling limitations will have to contend with poor surface visibility and with poor in-flight visibility. The horizon can be obscured, necessitating instrument guidance for safe flight. More powerful aircraft will be able to get above the dust but may have to fly a considerable distance to find a suitable airfield to land. Dust particles may cause damage to engine systems.

Dust storms are usually a daytime phenomena because low-level thermal instability and gustiness decrease at night.

13.8 Snow And Blowing Snow

Flying in moderate or heavy snow is equivalent to flying in cloud in terms of horizontal visibility. Even though air-to-ground visibility may be reasonable in snow conditions, the pilot should not be deceived into thinking horizontal visibility may be better at a lower level.

Pilots in Australia will not often encounter blowing snow (snow raised from the ground by wind). However, it can occur in the Australian Alps and the Antarctic. Because such conditions are associated with strong winds and poor visibility, landing may be hazardous.

13.9 Smoke

Smoke haze can be a serious hindrance to visual navigation. It reaches its peak during periods of prolonged anticyclonic weather, when light winds and subsidence inversions allow pollution levels to build up and for visibility to be reduced.

Burning of grasses during the dry season in northern parts of Australia can result in a pall of smoke, as depicted in Figure 13.6, which can persist over areas for many weeks.

Bushfires in southern Australia often inject thick smoke into the atmosphere, reducing visibility over wide areas and for prolonged periods.

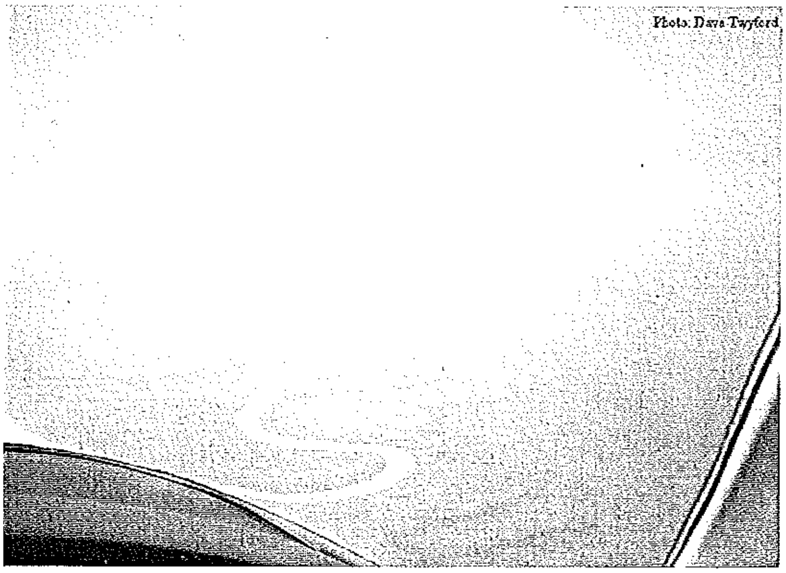


Figure 13.6
Extensive smoke haze over the Northern Territory during the dry season.
(Photo: © Dave Twyford)

MAJOR WEATHER SYSTEMS AND PATTERNS

Major weather systems are driven by the tendency for the atmosphere to correct for large-scale imbalances in the world's heat budget. These imbalances arise from the uneven exposure of the earth to the sun's radiation. It varies significantly between polar and equatorial regions, from day to day and season by season.

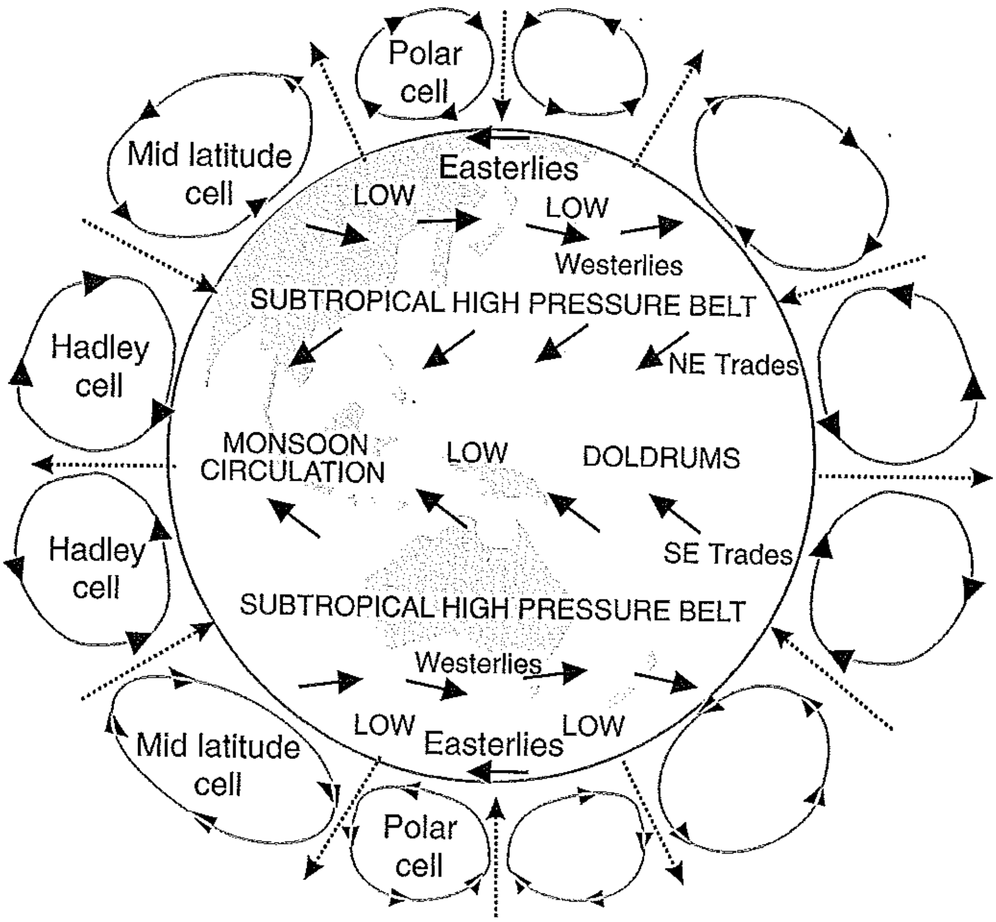


Figure 14.1

In this model of atmospheric circulations there are three major convective cells between the equator and poles. Easterly winds predominate near the equator and at the poles. Elsewhere westerly winds dominate. Surface low-pressure systems appear under the rising parts of the cells, with high-pressure areas under the descending parts.

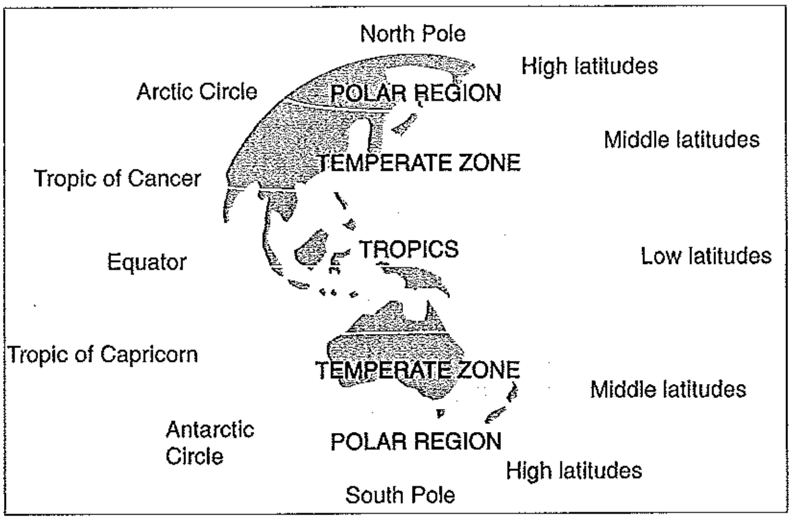


Figure 14.2
The major air mass source regions of the world; polar regions at high latitudes, temperate zones at middle latitudes and the tropical zone stretching across the equator.

Seasonal variations are clearly evident in the mid latitudes while, in the tropics, marked variations exist between wet and dry seasons.

These imbalances and rhythmic variations of radiation across the earth's surface lead to complex circulations of winds as illustrated in a simplified way in Figure 14.1. This figure depicts three cells between the tropics and the poles coincident with rising and descending air over surface low- and high-pressure zones.

These vertical circulations, combined with the rotation of the earth and the associated Coriolis effect, give rise to major pressure and wind zones. They are, starting at the equator and moving poleward:

- the doldrums in the equatorial trough;
- the trade winds (feeding out of the subtropical high-pressure belt and into the equatorial trough);
- the subtropical high-pressure belt;
- the westerlies;
- the belt of sub polar low-pressure systems.

The seasonal cycle is caused by the north/south movement of the sun shifting the latitude of the maximum heating/cooling regions.

The marked differences in the ability of land and sea surfaces to gain and lose heat lead to variations within this basic pattern.

14.1 Air Mass Source Regions

When air remains over a large uniform region for some days, it tends to acquire the characteristic temperature and moisture content of the surface below. If the air is colder than the underlying surface, it will be warmed. Similarly, dry air which remains over the ocean will be moistened. The effect of the surface may be distributed upwards through a layer several kilometres deep by the processes of conduction, convection and turbulence.

The properties of an air mass arriving at a point will depend on the original source region and on the properties of the surface. Any changes that may have occurred during transit will mainly be due to heating or cooling due to conduction, evaporation of moisture or drying of the airmass.

Air mass source regions are specified by the originating geographic zone (depicted in Figure 14.2) and whether it is continental or maritime. The source regions are:

- *tropical* - generally refers to warm air originating from tropical regions;
- *polar* - generally refers to cold air originating from high latitudes;
- *maritime* - If the source region is over water, the dew-point will be high;
- *continental* - If the source region is over land, the air will be relatively dry.

14.2 Classification Of Air Masses

In the Australian region three main types of air mass can be distinguished:

- Tropical maritime—Tm;
- Tropical continental—Tc;
- Polar maritime—Pm.

Figures 14.3 and 14.4 depict the source regions of the air masses and the general direction from which they reach or leave the Australian region.

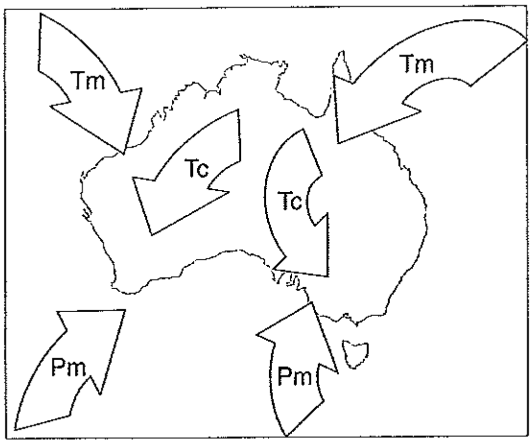


Figure 14.3
The three major air-mass types influencing Australia. Tropical maritime (Tm), Tropical continental (Tc), Polar maritime (Pm).

14.3 Modification Of Air Masses

An air mass will be modified by moving over:

- *a warm surface* - resulting in heating from below. Thermal instability then develops in the lower layers and distributes the heat upwards;
- *a cold surface* - this will cool the lower layers and increase stability;
- *a moist surface* - this will add moisture to the lower levels of the airmass;
- *a dry surface* - this will reduce the moisture in the lower levels of the airmass.

In general the characteristics of air masses change slowly. For instance, cool air penetrating the tropics will modify slowly. Some time will pass before it can be labelled as a tropical air mass.

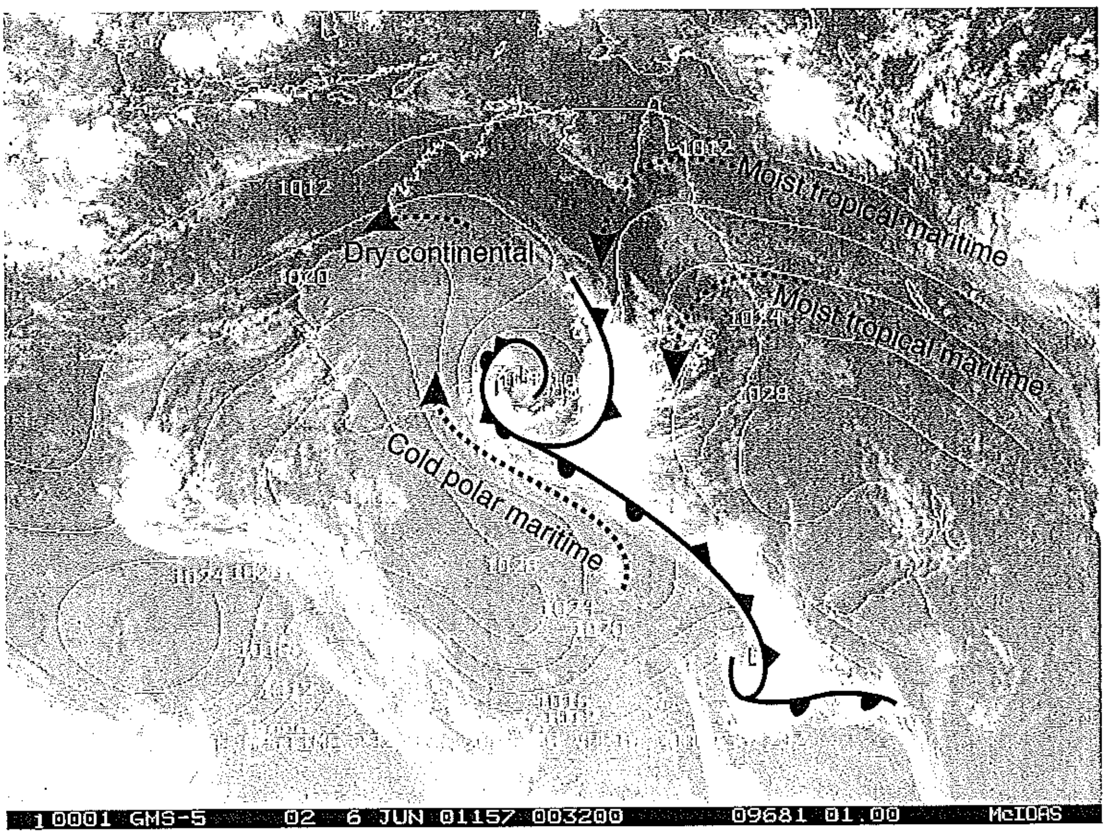


Figure 14.4
IR satellite image with air mass types, overlayed by a weather map and related frontal systems.

14.4 Main Frontal Zones

It is not always possible to find a definite boundary between two air masses. Often a gradual transition is observed over many kilometres. However when one air mass moves rapidly into another a distinct boundary becomes established. Such a boundary is called a front. Fronts are designated as cold or warm. When one front overrides or undercuts another an occluded front occurs. Refer to Section 14.9.

Cold fronts occur when cold dense air advances equatorwards from the poles, causing warm air to be forced aloft over the sloping surface of cold dense air.

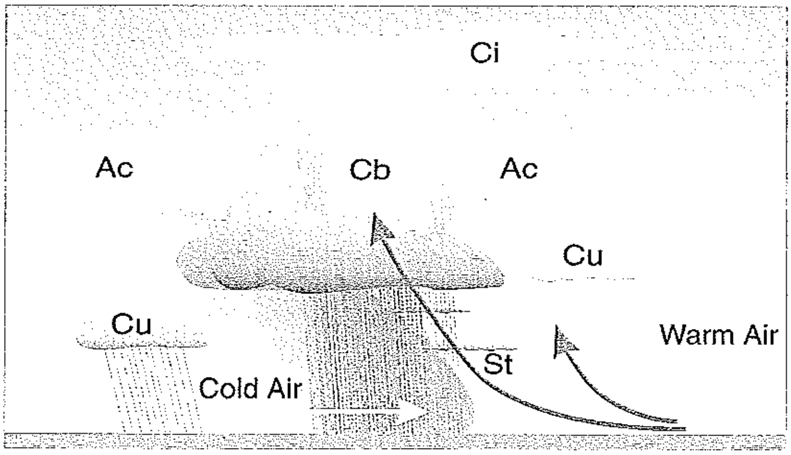


Figure 14.5

A cold front with a wedge of cold air undercutting warm moist air at a frontal zone. Ahead of the front, air is lifted to saturation. In an unstable atmosphere cumulonimbus clouds form near the front coincident with the zone of maximum lifting.

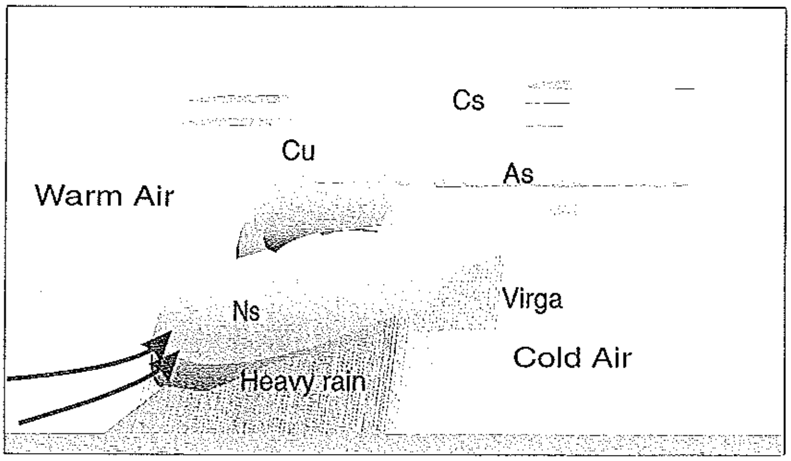


Figure 14.6

A warm front with warm air rising over cooler air, saturating and forming stratus and possibly cumulonimbus clouds with heavy rain. The frontal surface has a shallower slope than the cold front shown in Figure 14.5 and is therefore less likely to trigger active thunderstorms near the surface front.

Warm fronts occur when warm air of lower density moves polewards, sliding up and over cooler denser air.

In general cold fronts are steeper than warm fronts. On average a cold front has a slope of about one kilometre in the vertical over a distance of about 75 km. In the case of a warm front the slope is about 1 in 250.

The weather associated with fronts varies markedly. It depends on the characteristics of the air masses and the way in which they interact.

Cold and warm front models where developed by a number of meteorologists working at the Geophysical Institute in Bergen, Norway in the twentieth century. Although the models apply particularly to northern hemisphere they can be applied to the commonly observed southern hemisphere cold fronts and infrequently observed warm fronts.

14.5 The Model Cold Front

Cold fronts are characterised by cumulonimbus clouds, gusty turbulent winds, heavy rain and sometimes thunderstorms. When the cold front interacts with moist unstable air, a squall line accompanied by sudden showers and a vigorous wind shift may occur.

Within a very short distance a steep cold front produces the same amount of lifting as occurs over a much broader zone in advance of a warm front. It is therefore accompanied by a narrower band of cloud and precipitation than a warm front. The cloud and weather associated with a typical cold front are shown in Figure 14.5.

14.6 The Model Warm Front

If the warm air is moist, the approach of a warm front may first be heralded by a sheet of cirrus and cirrostratus cloud that continually becomes denser. Middle level clouds, such as altostratus and altocumulus, then appear.

Rain or snow may first fall as the altostratus cloud reaches its greatest density. Sometimes, however, precipitation evaporates before reaching the ground and virga can be seen below the main cloud base.

The precipitation intensifies as nimbostratus cloud develops. Lower clouds are also often present in the cold air. Evaporation of raindrops accompanied by turbulence leads to the development of these lower clouds.

The cloud and weather associated with an idealised warm front are shown in Figure 14.6.

14.7 Formation Of Polar Low-Pressure Systems And Fronts

Over middle and high latitudes low-pressure systems form along the marked discontinuity between the cold polar air and the warmer temperate zone air. As cold air moves north and warm air moves south waves develop along this boundary. Some of the waves undergo little or no change and eventually die out. However others increase in amplitude with great masses of polar and temperate/tropical air being carried away from their source regions. These waves may grow in amplitude until they eventually fold into closed low-pressure systems. Figure 14.7 depicts the development of a low in the southern hemisphere.

14.8 Weather Associated With Mature Low-Pressure Systems And Fronts

The weather associated with fronts depends on a number of factors, including the characteristics of the air masses and the way in which they interact with one another: in practice many variations may occur. For instance, if the warm air is dry and stable, cloud development may be limited and precipitation may not occur.

Consider the typical weather that would be experienced if traversing from Y to X at stage D in Figure 14.7.

- With the approach of the warm front there is a fall in pressure and an increase in cloudiness and precipitation, as well as in humidity.
- In the warm sector the cloudiness depends on the temperature, moisture and stability. The temperature, however, remains relatively warm but can depend on the

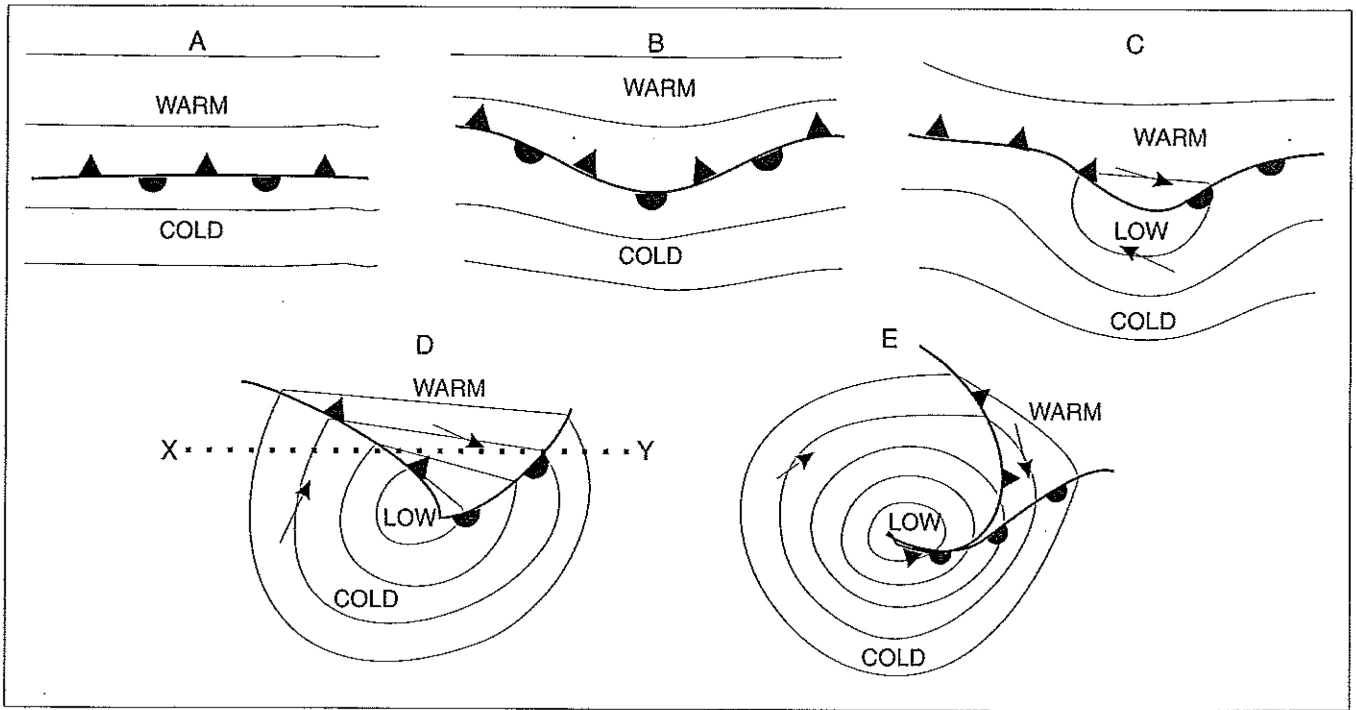


Figure 14.7

Development of a low-pressure system at middle and high latitudes is depicted by five illustrations. A and B show the front separating warm air from cold polar air with a wave beginning to form.

As the wave develops, a low of increasing intensity forms around it, as in diagrams C to E. The vertical cross section through XY is shown in Figure 14.8.

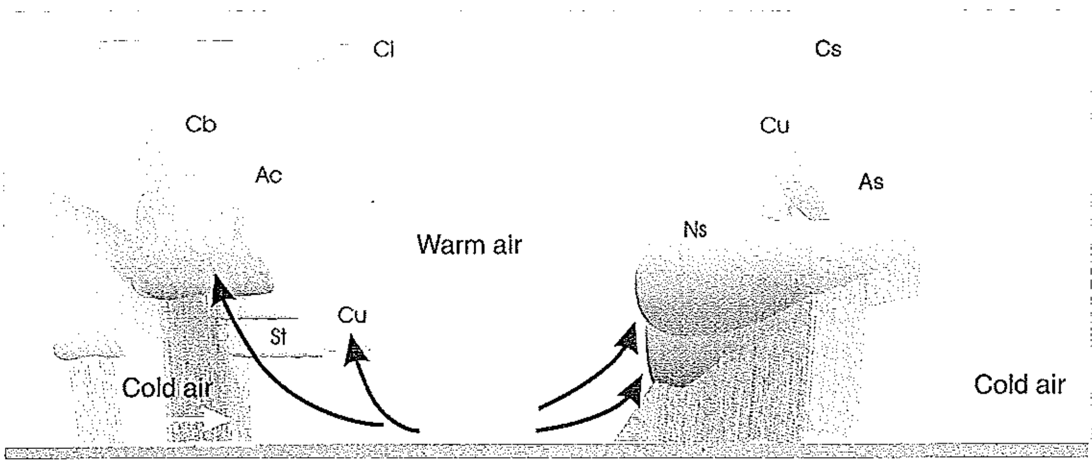


Figure 14.8
A cross section X to Y of Figure 14.7 D, through the warm sector and the warm and cold fronts.

amount of rainfall and cloudiness. The barometer shows a marked fall occurs as the cold frontal zone approaches.

- With the approach of an active well-developed cold front, the winds ahead of the front will begin to freshen with the approach of cumuliform clouds. The cloud base will become lower as the front comes closer and cumulonimbus clouds will develop with increasing precipitation.
- With the passage of the cold front a vigorous squall can occur with a sharp change in wind direction as the cold air arrives.
- A marked rise in pressure occurs immediately after the passage of the cold front and normally there will be rapid clearing of heavy showers. More isolated showers may continue if the air behind the front is moist and unstable.

Figure 14.8 depicts an idealised cross section X - Y through the frontal systems represented in Figure 14.7 D.

Figure 14.9 depicts a visible satellite image with cold, warm and occluded fronts. Cloud features associated with the systems are named.

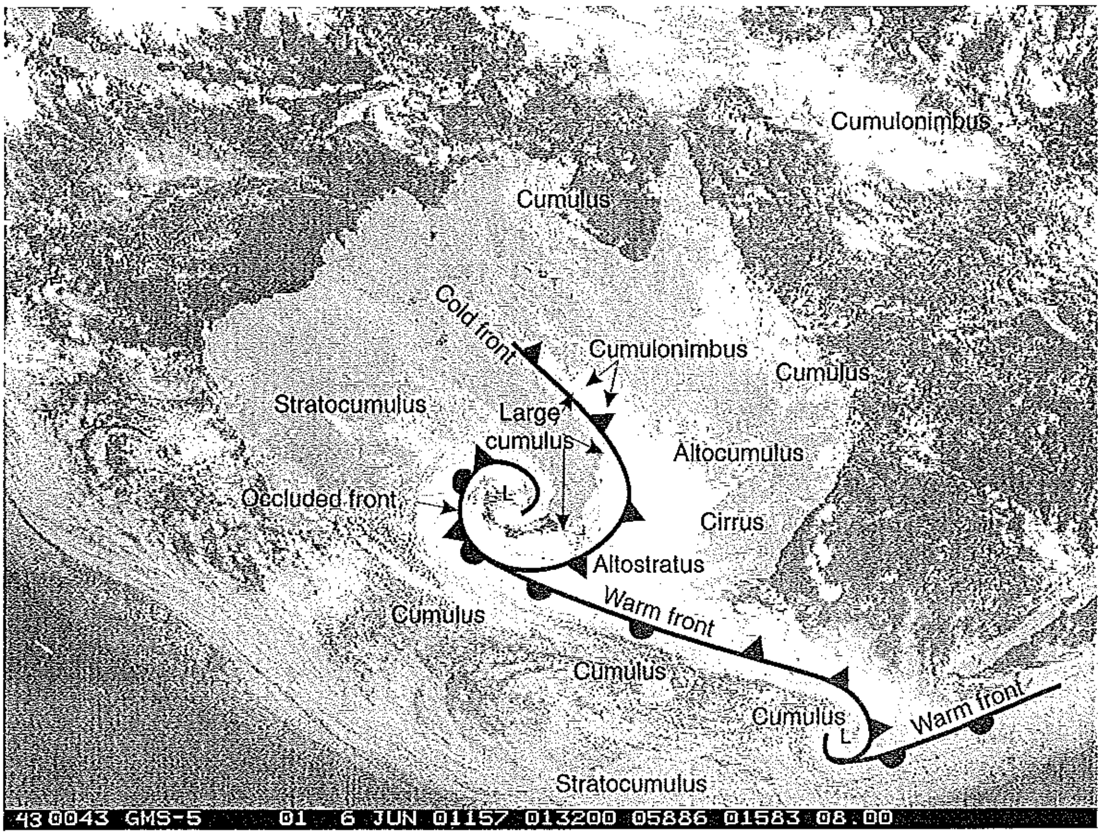


Figure 14.9
A visible satellite image with some frontal and cloud features marked.

14.9 Occluded Fronts

When a cold front moves faster than the warm front and overtakes it the warm sector between the two fronts is closed, forming an occluded front causing the original warm sector air to be lifted. Two different kinds of occluded fronts are possible.

If the air behind the cold front is the colder of the two cold air masses, it will undercut the cold air under the warm front. A cold front occlusion is produced in this way. Figure 14.10 illustrates how this may occur.

In Figure 14.10 a warm front occlusion is also shown. In this case, the air under the warm front is the colder of the two cold air masses. As a result, the air behind the cold front rides over the very cold air mass.

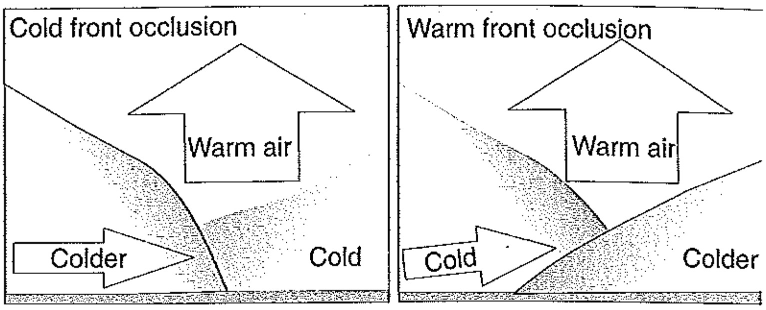


Figure 14.10
Occluded fronts. Cold air undercuts warmer air in a cold front occlusion while cold air overrides colder air in the warm front occlusion case. In both cases the warmer air is lifted.

14.10 Weather Associated With Occluded Fronts

In both types of occlusions warm air is pushed aloft. Clouds and precipitation will occur if there is sufficient lifting of the warm air.

Some of the characteristics of both cold and warm fronts may often be present, as is indicated in Figure 14.11 that depicts a cold front occlusion.

In practice, more complex cloud and precipitation patterns occur. However, the model provides a useful guide to the atmospheric processes that occur.

14.11 Weather Maps

The weather map is compiled from hundreds of weather observations taken simultaneously (synoptic data).

Its dominant features are the smooth, curving patterns of sea level isobars - lines of equal atmospheric pressure adjusted to mean sea level. The weather map is used to identify weather systems such as highs, lows (including tropical cyclones), fronts and troughs.

The weather map is a fairly simple representation of the location of the larger

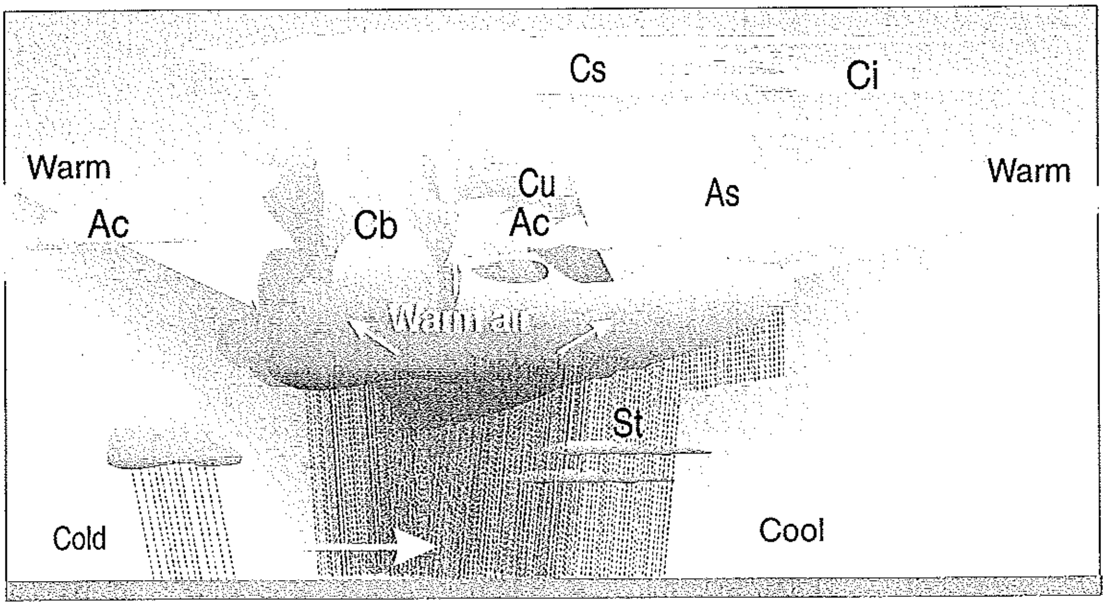


Figure 14.11
Cold front occlusion.

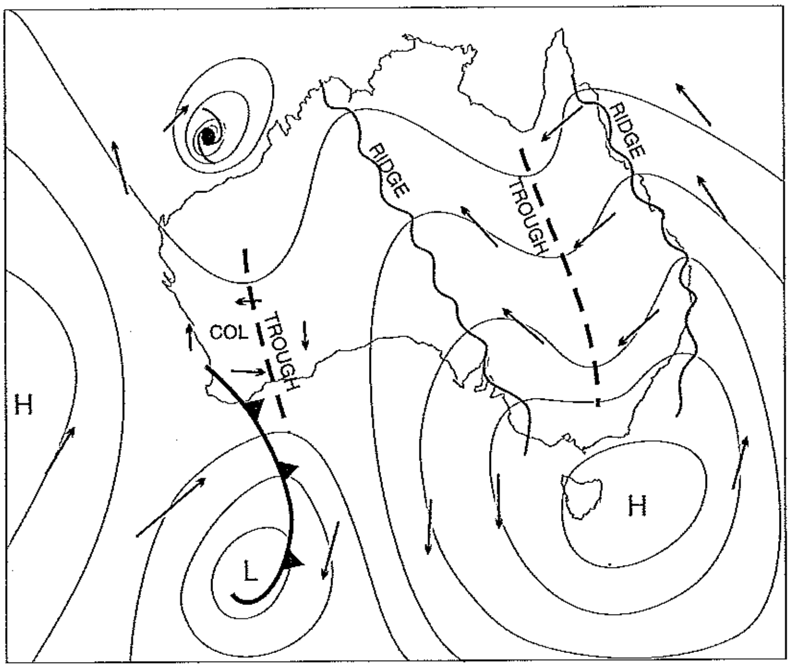


Figure 14.12
Mean sea level analysis patterns showing surface wind direction.

surface weather systems. As such the weather map does not and cannot show all weather features and in particular will not show local variations of importance to aviators. For example the isobar spacing will not give a good indication of wind speed when decoupling of winds at low levels has occurred, as discussed in Chapter 9.

Nevertheless weather maps provide a useful guide to the weather and are particularly valuable when used in conjunction with aviation area (ARFOR) and terminal (TAF) forecasts.

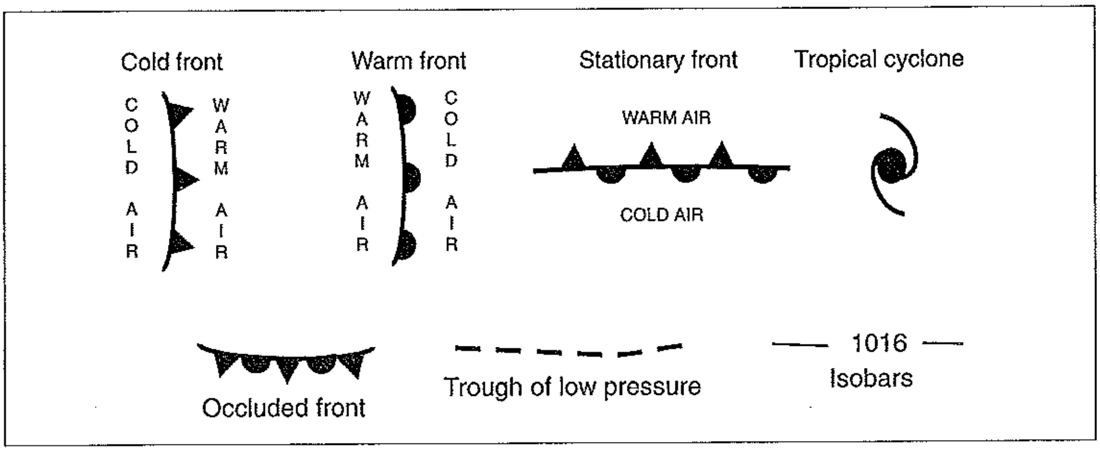
Typical features illustrated on weather maps as depicted in Figure 14.12 are:

- *a high or anticyclone* – a closed area of high pressure with centre designated by H;
- *a ridge of high pressure* – an elongated area of high pressure;
- *a low* – a closed area of low pressure with centre designated as L (sometimes called a cyclone but in Australia the term cyclone is reserved for intense tropical low-pressure systems);
- *a trough of low pressure* – an extended area of low pressure not associated with a front;
- *a col* – a region between two high and low-pressure systems;
- *a tropical cyclone* – a non-frontal low-pressure system that develops over tropical waters with winds in excess of 34 knots.

Lines and symbols on weather maps (Figure 14.13):

- *cold front* – represented by a line faced with barbs pointing in the direction of movement;
- *warm front* – represented by a line with semicircles pointing in the direction of movement;
- *stationary front* – represented by a line with alternating, back to back, barbs and semicircles. In this case, the wind flow will be parallel to the frontal zone, and on the synoptic chart the stationary front will be parallel to the isobars;
- *tropical cyclone* – represented by two swirls flowing into a black circle;
- *an occluded front* – represented by a line with semicircles and barbs pointing in the direction of movement;

Figure 14.13
Typical lines shown on weather maps.



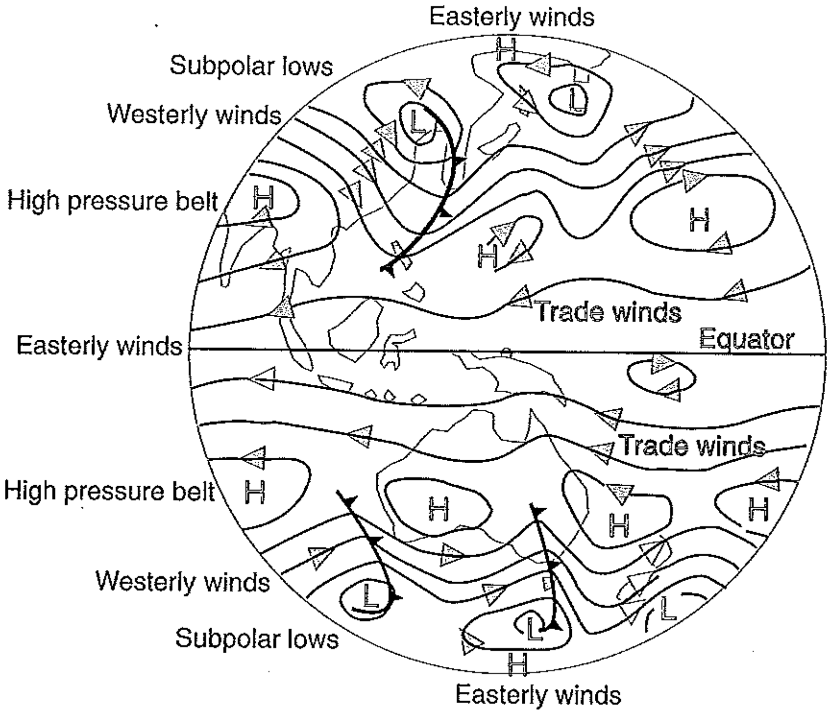


Figure 14.14
General wind regimes and pressure patterns.

- *a trough of low pressure* – represented by a dashed line;
- *isobars* – represented by thin lines interrupted by the pressure value.

14.12 Global Wind Regimes and Weather Patterns

Some of the typical features of the weather patterns depicted in Figure 14.14 are:

- Easterly winds over the tropics and subtropics. Important features of the tropical easterlies include the southeast and northeast trade winds, monsoon lows and sometimes tropical cyclones (known as hurricanes in the Americas and typhoons in Asia).
- High-pressure belts in the mid latitudes contain centres of varying strengths that generally move from west to east. Fluctuations in the intensity of highs (anticyclones) strongly influence the behaviour of the trade winds and the development and decay of tropical lows.
- Westerly winds on the polar side of the high-pressure belts with embedded fronts and troughs traveling from west to east.
- Subpolar lows usually centred between latitudes 50-60 degrees south and north.
- A high-pressure area over Antarctica associated with extremely cold and dense air, is ringed by easterly winds that form the boundary with the subpolar low-pressure belt.

These features vary in intensity and location according to the season. For instance, in austral summer the high-pressure belt is usually found just south of Australia, while the subtropical easterlies cover most of the continent. Monsoon flows and associated lows over the tropics bring significant summer rain to the north (the wet season) and tropical cyclones may develop. In austral winter the high-pressure belt is usually located over the continent, allowing westerlies and strong cold fronts to affect southern Australia.

It is important to understand that significant exceptions can occur. For example when strong high-pressure systems move slowly across the oceans well south of Australia, closed or 'cut off' lows may then move across southern Australia or intensify over the Tasman Sea causing prolonged heavy rain.

All weather systems have a life cycle of development, maturity and decay. They occasionally become stationary or even reverse their usual direction of travel.

14.13 Studying Forecast Weather Maps

The forecast weather map is called the prognostic chart, often refered to as the PROG. The transient nature of weather systems is clearly evident in the four panel prognostic patterns illustrated in Figure 14.15. Studying these weather maps we see a combination of isobaric patterns and frontal systems continuously changing. Of interest is the progression of systems, generally from west to east in southern Australia. A summary of weather conditions experienced at 9 pm for major centres is tabulated in Table 14.1.

REMEMBER: Prognostic weather charts should be used with some caution, as errors do occur due to limitations in data, the forecast computer models, and the inherent complexity of the atmosphere.

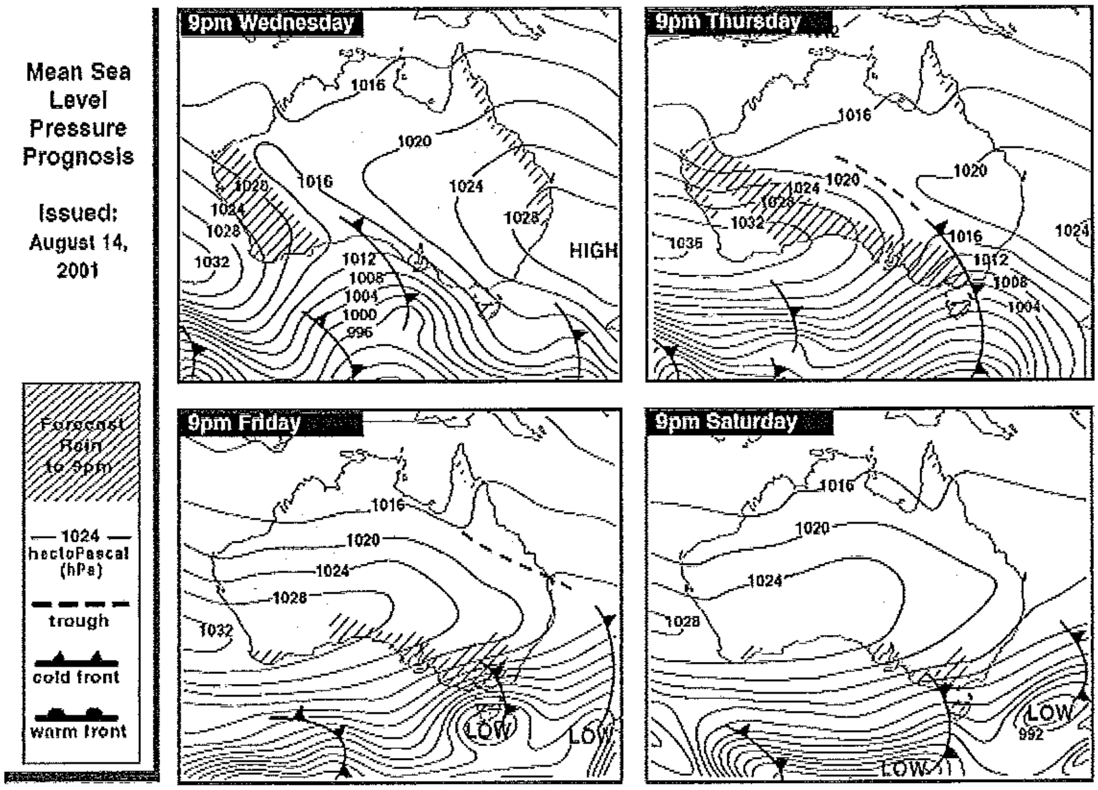


Figure 14.15
A sequence of four winter time surface weather charts.

	9 pm Wednesday	9 pm Thursday	9 pm Friday	9 pm Saturday
Perth	Southerly winds. Showers.	Light Southerly winds. Overnight Fog.	Light Southerly winds. Overnight Fog.	Light variable winds. Fine.
Adelaide	Strong northwest winds. Fine.	Strong southwest winds. Showers.	Strong southwest winds. Showers.	Strong southwest winds. Showers.
Melbourne	Strong northwest winds. Fine.	Strong southwest winds. Showers.	Very strong southwest winds. Showers.	Strong southwest winds. Showers.
Sydney	Light northwest winds. Fine.	Moderate northwest winds. Fine.	Strong southwest winds. Fine.	Moderate southwest winds. Fine.

Table 14.1
Summary of observed weather at 9 pm for major centres.

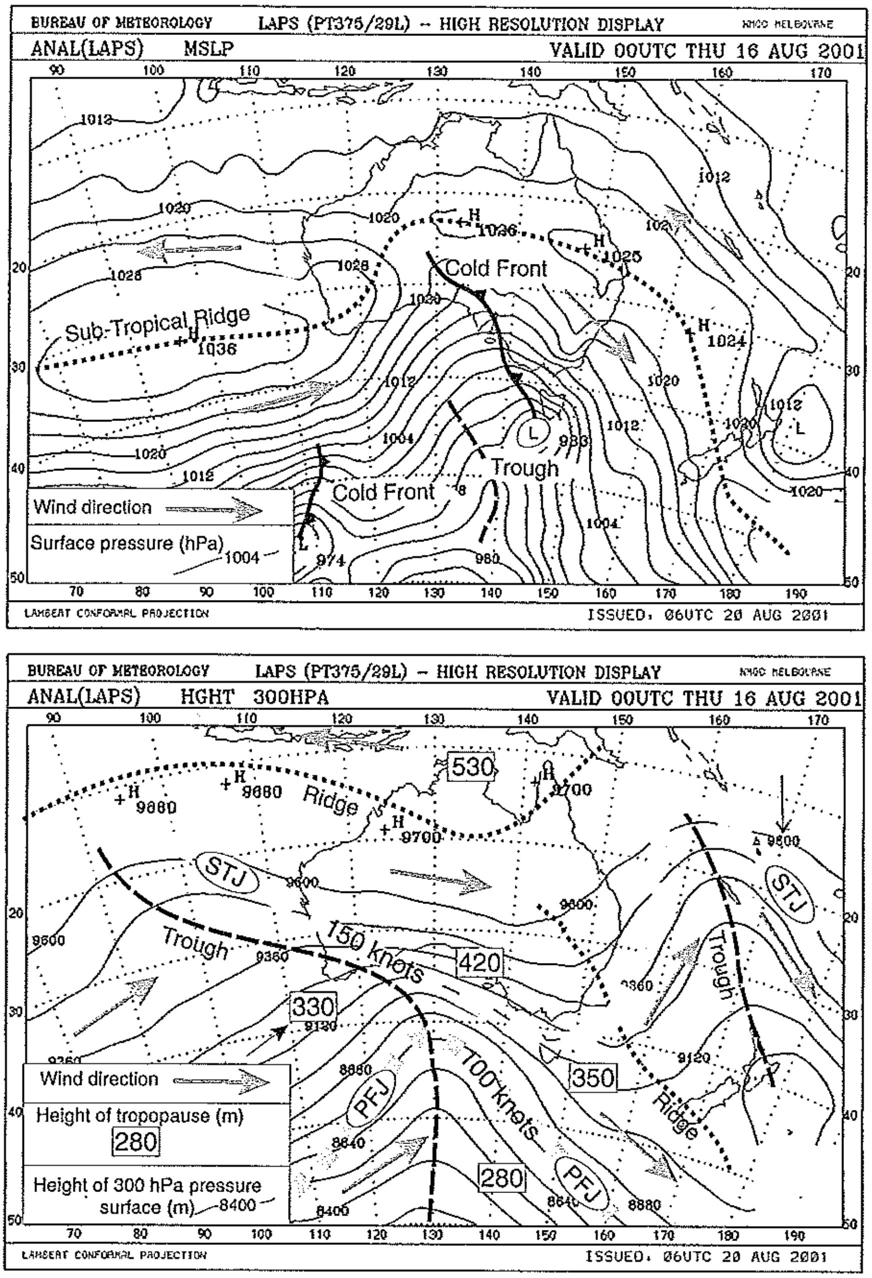


Figure 14.16
Surface and 300 hPa weather patterns for 16 August 2001.

14.14 Upper Level Circulations

The closed circulation systems (highs and lows) and clearly defined troughs and fronts common at mean sea level tend to disappear or be smoothed out in the upper air. Upper-level features tend to lag behind surface features, i.e. an upper trough associated with a surface front will lie further westward. Furthermore winds tend to increase with height up to the tropopause where jet streams are common (see Chapter 9 section 17).

Figure 14.16 depicts the surface and 300 hPa weather charts for 16 August 2001. The surface chart shows the wind north of the subtropical ridge has an easterly component and south of the subtropical ridge with a westerly component. Along the subtropical ridge winds are light and variable. The 300 hPa chart depicts the axis of the subtropical and polar jets, the height of the tropopause and 300 hPa surface and jet stream maximum wind speeds (at 300 hPa).

By comparing the two charts in Figure 14.16 differences can be seen in the flow pattern between low and high levels. There are of course many variations between these two levels. Some of the features to look for are:

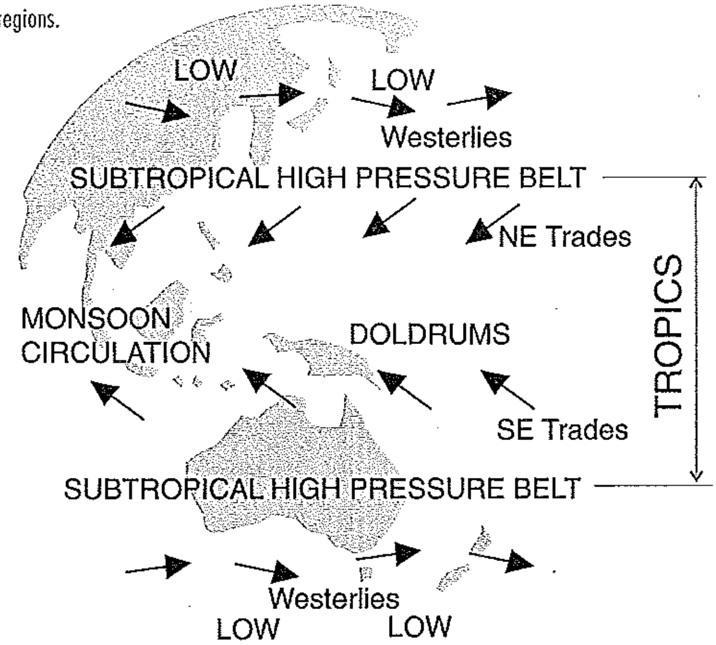


Figure 14.17
Convenient tropical regions.

- the closed circulations at the surface and the broader features at higher levels;
- the location of surface features compared to those at higher levels;
- the shift in the position of the subtropical ridge;
- the wind speeds near the surface compared to those at 300 hPa including the sub-tropical jet stream.

14.15 Tropical Weather Patterns

Broadly speaking, the tropics span the lower latitude areas of the earth where most heat energy is received from the sun. Large scale currents in the oceans and weather systems in the atmosphere develop in response to this imbalance in order to redistribute the excess heat polewards. The tropics are defined geographically as the area between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S) (Figure 14.2); within this zone the sun is directly overhead during some part of the year.

However, in meteorology it is more convenient to define the tropics as that region equatorward of the belt of high pressure (Figure 14.17), i.e. the belt of high pressure that circles the globe between 25°-45° latitude. This belt contains several separate high-pressure cells (or anticyclones) that move north and southward with the seasons.

14.16 The Hadley Cell

In simple terms, the Hadley cell is a large-scale circulation consisting of warm air rising near the equator moving poleward in the upper troposphere before gently sinking (subsiding) to form the subtropical high-pressure belt (Figure 14.18). Surface winds

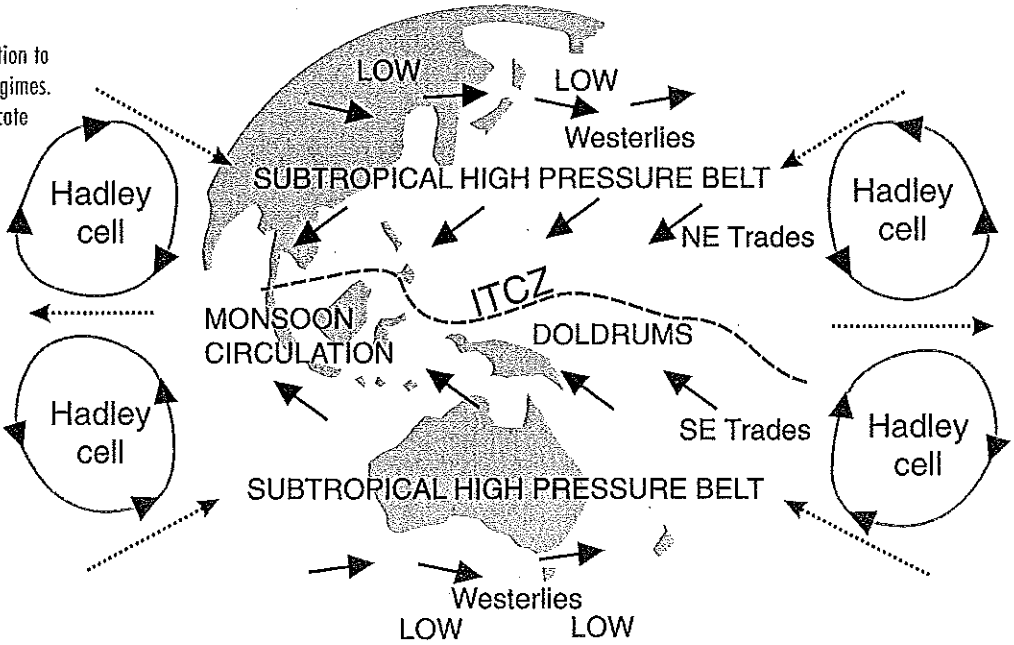


Figure 14.18
Hadley cells in relation to the general wind regimes. Dashed arrows indicate vertical motion.

flowing equatorward from the subtropical ridge, are deflected westwards by the Coriolis effect forming the so-called trade winds (southeast winds in the southern hemisphere, northeast in the northern hemisphere). These winds converge near the equator into the Intertropical Convergence Zone (ITCZ) within a zone of low pressure called the near-equatorial trough: this area is the location of the upward branch of the Hadley cell.

During the year, the Hadley cells in each hemisphere move north and south in response to the position of the sun relative to the earth. The location of each cell is also influenced by the temperature differences arising from the uneven distribution of land and sea surfaces in each hemisphere. The oceans, which cover more than 70 per cent of the earth's surface, have a higher heat capacity than the continents and thus heat and cool more slowly. Temperature fluctuations are therefore much less over the oceans and movements of the Hadley cell are relatively small. Conversely, the very large seasonal changes in temperature over the continents results in substantial movement of the Hadley cell.

The descending air of each Hadley cell reaches the earth's surface in the subtropical high- pressure belt of each hemisphere. The centre of each belt of high pressure also moves north and south about a mean position at about latitude 30°.

Although the average seasonal positions of the Hadley cell are well marked, especially in monsoonal regions, there are often large variations from week to week and day to day.

14.17 The Sourthern Oscillation

In addition to the Hadley cell, there is also an east-west vertical circulation in the Australia-Pacific region known as the Walker circulation (Figure 14.19). The Pacific Ocean, which covers about one-third of the earth's surface, is significantly warmer on the western side than the eastern side near South America. This gives rise to a zonal circulation with the rising branch over the Indonesian "maritime continent" to the northwest of Australia, and the descending branch over the eastern Pacific Ocean.

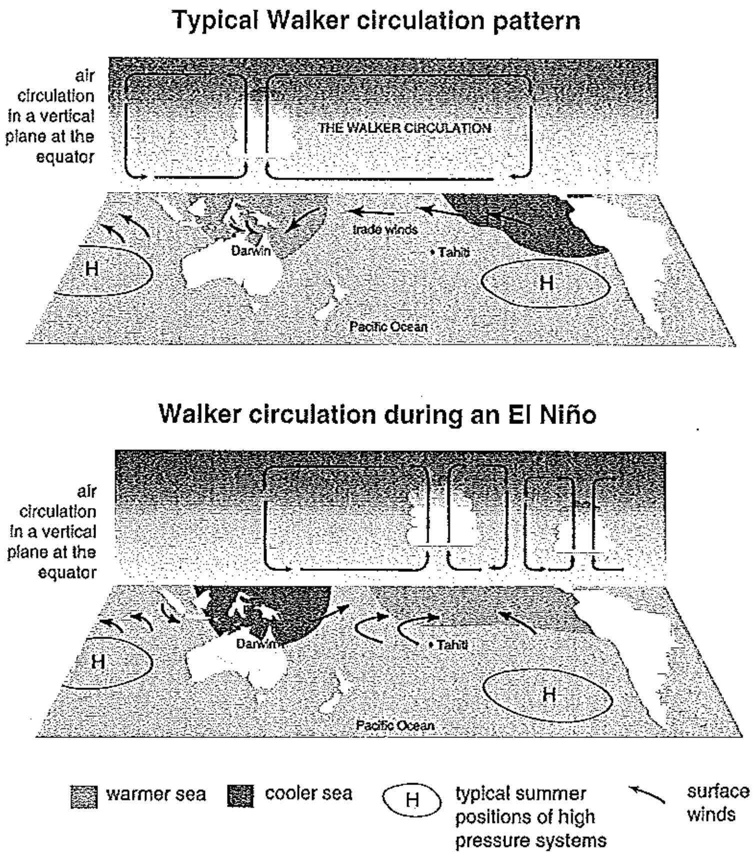


Figure 14.19
The Walker circulation.

At intervals of several years, the temperature gradient across the Pacific Ocean is reduced. The seas north of Australia cool as the warm water moves eastward into the central Pacific, while the cold current off South America warms by 5 degrees or more. Pressures become higher than normal over the western Pacific and lower over the eastern Pacific. This pressure variation is called the Southern Oscillation, one measure of which is the departure from average of the pressure difference between Darwin and Tahiti (the Southern Oscillation index or SOI). The rising branch of the Walker circulation moves eastwards enhancing upward motion in the central and eastern Pacific suppressing the monsoon in the Australia-Indonesian area. This phenomenon has become well known in recent years as El Niño. It can cause dramatic changes in the world's weather: drought conditions prevail in Africa, Australia and South-East Asia and monsoon rains are generally much reduced. Meanwhile there are increased numbers of tropical cyclones in the central Pacific and increased rainfall and potential for flooding in the Americas.

The converse phenomenon, when waters become warmer than normal over the western Pacific and colder in the east, has been named, La Niña. Pressures are lower than normal and the upward branch of the Walker circulation is enhanced over the western Pacific, with increased subsidence and higher pressure over the eastern Pacific. This results in a more active monsoon and increased rainfall over the Indonesia-Australian region, and drought conditions are exacerbated in the central and eastern Pacific

The combined cycle in the atmosphere and ocean has become known as the El Niño Southern Oscillation (ENSO) phenomenon.

14.18 The Equatorial Trough

The trade winds of each hemisphere blow equatorward from the subtropical high-pressure belt towards a zone of relatively low pressure. This is known as the equatorial trough. The mean position of the centre of the equatorial trough is not at the equator, but at about latitude 5°N.

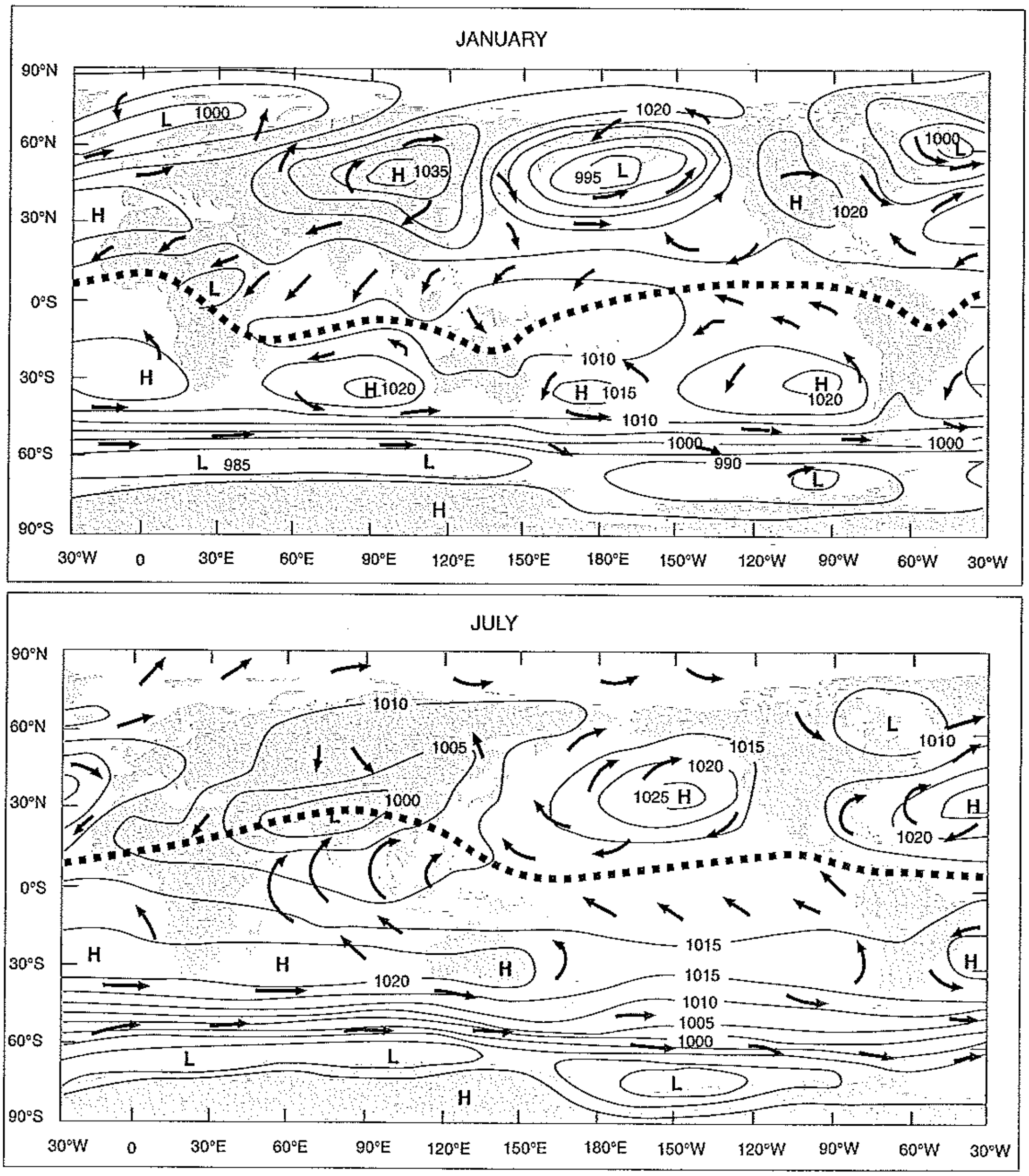


Figure 14.20
Average January and July sea-level pressure distributions and surface wind flow patterns. The dashed line represents the position of the Intertropical Convergence Zone (ITCZ).

14.19 The Average Mean Sea-Level Circulation

As discussed earlier, pressure systems move north and south with the apparent motion of the sun relative to the earth. The two extreme positions of the axis of high and low pressure occur on average in January and July.

In lower latitudes, the Coriolis force (see section 9.3) becomes very small (decreasing to zero at the equator) and the time-scale for geostrophic balance is large. Therefore the pressure gradient force dominates and there is a relatively large cross-isobar component of flow towards low pressure i.e. towards the equatorial trough. Often the pressure gradients are weak and the wind is then strongly influenced by local effects (e.g. sea-breezes, topography) and friction.

When an airstream crosses the equator and enters the other hemisphere, the Coriolis force increases with latitude, but the direction of the deflection is reversed. The easterly trade winds therefore tend to change to equatorial westerlies after crossing the equator on their way towards the equatorial trough. This effect can be seen in Figure 14.20. In some regions (e.g. the Atlantic), easterlies may occur on both sides of the equatorial trough. In these areas the equatorial westerlies are absent.

Figure 14.20 depicts for January and July the monthly mean wind flow around the earth and the position of the ITCZ along different meridians. Notice that the ITCZ passes over northern Australia and Southern Africa in January. Later in the year it moves northwards and extends over South-East Asia and Northern Africa in July. Larger movements occur in these regions than elsewhere because deep heat lows develop over these continents.

The average monthly MSL pressures and the corresponding wind patterns conceal the daily variations that occur. Nevertheless, they provide a useful background in understanding tropical meteorology.

14.20 The Trade Winds

Most of the regions between the subtropical high-pressure belts and the equatorial trough are occupied by the trade winds. In the southern hemisphere Coriolis deflection towards the left produces the southeast trade winds. Similarly in the northern hemisphere the air moving equatorward is deflected towards the right by the Coriolis force and the northeast trade winds develop.

The winds do not necessarily blow exactly from these directions. Differences in pressure gradients and the Coriolis force cause the wind direction and speed to vary from time to time and from place to place. Nevertheless, the trade winds are generally noted for their persistence and steadiness.

Over ocean areas the trades are characterised by cumulus clouds with bases at about 3000 feet and tops at 6000 to 9000 feet. On coastlines facing the trade winds, the vertical cloud development is greater and there is a tendency to showers, especially if the wind speed increases or there is elevated terrain. On the other hand, the lee side of mountain ranges may sometimes be almost free of low clouds.

The restricted cloud development and the generally fine weather associated with the trades are linked with the trade wind inversion caused by subsidence associated with the subtropical high-pressure belt. This inversion places a 'lid' on cumulus development, especially over ocean areas.

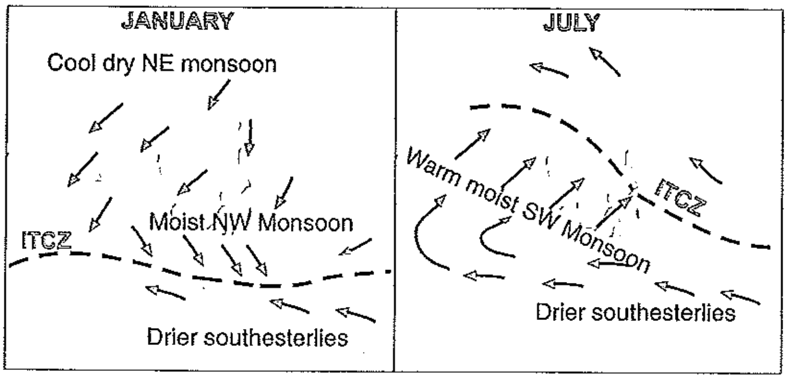
However, as the air moves equatorward over warmer seas, the trade wind inversion level begins to rise and weaken and low-level moisture increases. Vertical cloud development then increases as the instability extends to greater altitudes. Precipitation becomes heavier and more frequent in the vicinity of the equatorial trough.

14.21 The Monsoons

Continents tend to warm up quickly in summer and to cool rapidly in winter, in contrast to the seas which maintain a more even temperature throughout the year. When large continental and ocean areas are involved, atmospheric circulations may develop on a large scale. This is particularly true of the monsoon wind pattern that in simple terms may be thought of as a huge sea-breeze-like circulation linking the summer and winter hemispheres. Meteorologically, the defining characteristics of a monsoon are the persistence of the prevailing surface wind flow and its seasonal reversal. Although it strictly relates to the wind field, the term 'monsoon' tends to have a colloquial connotation relating to the associated cloud and heavy rainfall.

In early summer in Australia, air from the winter (northern) hemisphere begins to flow from the oceans towards the hot continent. Moist maritime air crosses the coastline and becomes more and more unstable as it is heated from below. By the time of the summer solstice, heating of the surface is at a maximum. Strong pressure gradients due to decreasing pressure in the monsoon trough accelerate the poleward moving airstream and strengthen the low-level wind speed, while the Coriolis force induces a marked westerly component to this flow. The anticyclones in the upper atmosphere, above the surface trough, also intensify; the Coriolis force acting on the equatorward moving air produces a cross-equatorial easterly flow of jet-stream strength. Great vertical cloud development occurs, often accentuated by the presence of mountain ranges; deep layers of stratiform cloud are also present. Frequent heavy rain, thunderstorms and violent squalls take place over wide areas of the continent and adjacent ocean areas.

Figure 14.21
Monsoon regions.



In winter, over Australia, the situation is reversed. High pressure dominates over the cooler land and air flows offshore and equatorward. Subsidence is widespread, the air is drier and the weather is generally fine.

14.22 Monsoon Regions

The main monsoon regimes are in the tropical areas of Africa, India, eastern Asia, and Indonesia-Australia, the best developed being over southern and eastern Asia (Figure 14.21). In December-January, the outflow from the winter Siberian high-pressure system leads to northerly or northeasterly flow across southern China, Burma and India. The air then moves across the Indian Ocean towards the equatorial trough lying south of the equator. The Siberian anticyclone weakens in March as the sun moves northward and land temperatures begin to rise.

In northern Australia the 'dry season' occurs during the southern hemisphere winter when south-east trade winds extend over the region. In spring, rising temperatures gradually lead to the establishment of an inland heat low, southward movement of the subtropical ridge and a weakening of the southeast trades.

From about October the 'wet season' commences with isolated thunderstorms in the moist air north of the heat low over northern parts of the continent. The northwest monsoon normally arrives over the north-western and northern regions of Australia in late December. Widespread stratiform cloud with heavy rain, embedded thunderstorms, and violent squalls may persist for several days. The heaviest precipitation usually occurs between January and March when the monsoon trough is well established over the northern part of the continent. During April, the monsoon trough retreats northward and isolated thunderstorms occur over the land in the moist unstable easterly airflow. By May, southeast trade winds become established once more as the subtropical ridge migrates northward.

14.23 The Monsoon Trough

The monsoon goes through a series of active and non-active cycles over a varying time-scale in the order of a few weeks. Active periods are characterised by fresh westerly winds in a deep layer (up to the mid-troposphere) with more widespread and heavy rainfall. Break periods have weaker and shallower westerly winds with little or no deep stratiform cloud and generally isolated or scattered thunderstorm activity; falls may be locally heavy but the rain is not widespread.

The monsoon trough is the breeding ground for low-pressure systems and tropical cyclones in the Pacific and Indian Oceans. Whenever the trough is over warm water, there is a risk of tropical cyclone formation.

14.24 Weather In The Tropics

The temperature in the tropics varies much less from summer to winter than it does in higher latitudes. This is mainly due to the fact that the midday sun is never far from its zenith.

Another factor is that oceans cover most of the tropics. The annual temperature variations of the oceans are relatively small, being less than 3°C almost everywhere in the tropics. Even over the tropical continents the annual range of mean monthly temperature is less than 10°C. By contrast, it is 15°C or more elsewhere.

The apparent annual movement of the sun between the Tropics of Cancer and Capricorn results in the tropics experiencing the midday sun directly overhead twice during the year. In some areas this leads to two periods of above-average temperature, although the opposite effect may occur when cloud and precipitation reduce the temperature.

In general, horizontal temperature gradients in the subtropical high-pressure belts are considerably weaker than those observed in the poleward westerlies. As a result, cold fronts are often less well-defined than those in middle latitudes. The temperature discontinuities across fronts weaken as they move toward the equator. Fronts extending into the trades are often more easily identified as a 'surge' of stronger winds associated with the high pressure behind the front and sometimes as a wind shear line. These surges are strongest in winter and are responsible for episodes of strong winds over the tropical oceans. In the spring and early summer, fronts can trigger widespread tropical thunderstorm activity when they reach the moist unstable air over northern Australia.

14.25 Convergence Zones

Although frontal activity is rarely evident in the tropics, widespread cloud and rain frequently occur. Low-level convergence in a depression or trough causes the air to rise leading to convective cloud development and precipitation. This effect is accentuated if divergence takes place in the upper troposphere, for example ahead of an upper-level trough. Convergence may also occur when two air streams approach each other from different directions. This pattern often occurs on a small scale with sea breezes and thunderstorm outflow boundaries. When moist tropical air is forced to rise, organised lines of cumulus or cumulonimbus clouds may develop in the vicinity of the convergence zone.

14.26 Weather In The Equatorial Trough

The equatorial trough is a region of light and variable winds (known as the doldrums). Local thunderstorms may develop due to surface heating and orographic effects over land and localised low-level convergence over the sea. Rain squalls also occur.

Convergence zones within the equatorial trough may lead to more widespread cloud and precipitation. The tops of cumulus and cumulonimbus clouds spread out at higher levels and form sheets of altostratus and cirrostratus cloud. While rain from thunderstorm cells can be very heavy, it only occurs over relatively localised areas. The less intense rain from the altostratus cloud may fall over wide areas and for longer periods and is responsible for the larger proportion of tropical rainfall.

14.27 The Intertropical Convergence Zone

Convergence occurs on a very large scale when the trade wind systems of each hemisphere meet in a narrow zone. This is known as the intertropical convergence zone (ITCZ). It can occur where the northeast and southeast trade winds approach each other and also in the westerly wind zone straddled between two near-equatorial troughs.

The ITCZ can produce extremely bad weather conditions over a wide area. Vertical cloud development extends through the troposphere to the high tropical tropopause (at altitudes of 55 000 feet and more). The cloud base may be down to a few hundred feet. The zone of bad weather may sometimes be several hundred kilometres in width with general heavy rain, frequent thunderstorms and violent wind squalls.

14.28 Diurnal And Local Effects

Diurnal and local effects are very important in the tropics. They can exert a greater influence on the weather than synoptic scale disturbances. Topographic effects often accentuate diurnal variations in temperature, wind and rain.

Variations in temperature that occur throughout the day depend largely on the prevailing wind direction. Where steady on-shore winds occur, the daily range of temperature is small. By contrast, the climate may be of a continental type if the prevailing wind is off-shore and a relatively large range of temperature may occur.

The sea-breeze has an important effect on the temperature and precipitation in the tropics. It can also reinforce a prevailing on-shore wind. In regions where the air is moist and unstable, the sea breeze can lead to increased vertical motion, resulting in afternoon showers or thunderstorms. In a similar way, a land breeze may produce off-shore thunderstorms around dawn.

14.29 Tropical Disturbances

The term tropical disturbance refers to any feature of the flow that is associated with active convection. These are easily identified on a satellite image as persistent cloud clusters or areas of cloudiness on a satellite photograph. The most vigorous tropical disturbances are the intense cyclonic storms that form over warm tropical waters.

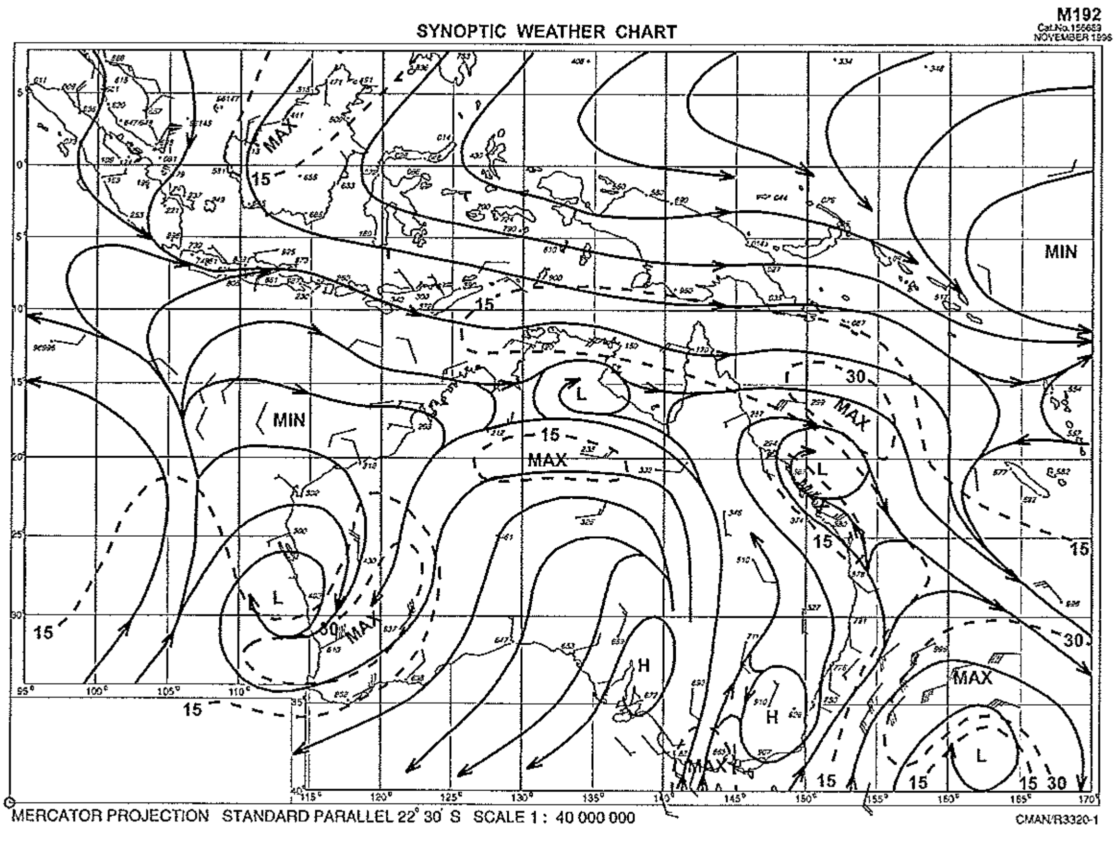


Figure 14.22
Streamline and isotach analysis.

14.30 Tropical Weather Analysis And Forecasting

Streamline and isotach analysis is generally used in the tropics because isobaric charts do not satisfactorily represent the wind field. A streamline is a line which is parallel to the direction of the wind at all points along it. Daily synoptic streamline charts show many features which are absent from mean annual or monthly charts owing to the smoothing which occurs when average values are taken. An isotach is a line that joins points of equal wind speed.

A number of characteristic streamline patterns can be identified on streamline synoptic charts. In addition to the broad wind streams associated with straight or curved flow, there are so-called singularities i.e. outdrafts (outflows associated with anticyclones or highs), indrafts (inflowing cyclonic circulations), neutral points (areas of light wind equivalent to cols in isobaric charts) and wave patterns and convergence zones. Isotachs are contours of constant wind speed superimposed on the streamline. Thus the wind velocity can be determined at any point in a streamline-isotach analysis or prognosis chart. Figure 14.22 depicts a typical summer streamline chart.

14.31 Tropical Cyclones

Tropical cyclones are non-frontal low-pressure systems that develop over the warm (greater than 26°C) waters of the tropics. Tropical cyclones do not form near the equator. They usually develop within the latitude band 5°-20° but can develop as far as 30° from the equator. A tropical low is classified as a tropical cyclone when the maximum mean winds around the centre reach gale force (average winds 34 knots or more). In Australia, the term 'Severe Tropical Cyclone' is used when the maximum winds reach hurricane force (64 knots or more). In other parts of the world, a tropical cyclone is called a 'tropical storm'; a 'severe tropical cyclone' is called a 'hurricane' in the Americas and a 'typhoon' in the northwest Pacific. Tropical cyclones typically extend to the tropopause at altitudes of up to 70 000 feet and range in size from about 80 to 500 km diameter but may be over 1000 km in diameter. Their lifetime cycle can range from one to thirty days with an average of six to seven days. The structure of a cyclone is depicted in Figure 14.23.

In the southern hemisphere the cyclone season runs from November to April with the peak in January to March. In the northern hemisphere the cyclone season runs from June to November, with the peak in August to October. Outside these seasons, tropical cyclones are rare.

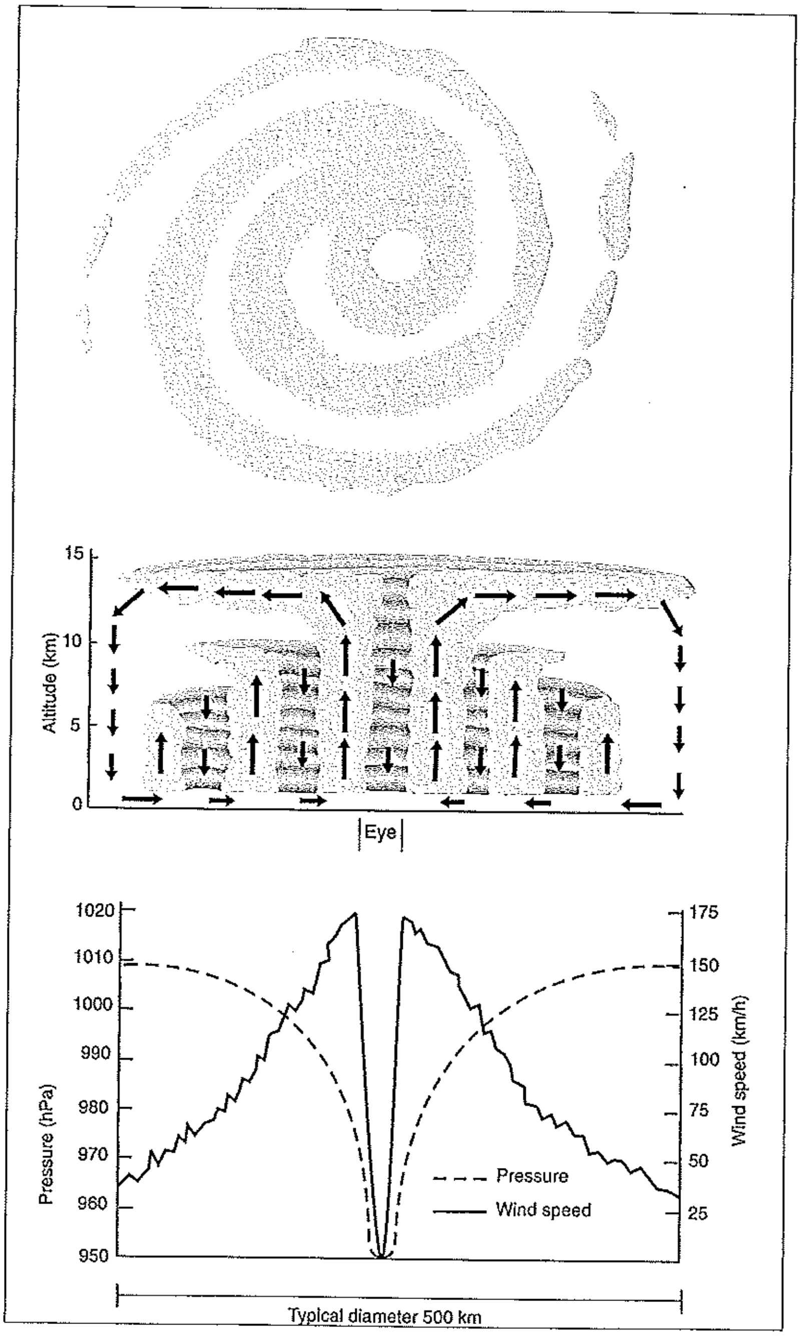


Figure 14.23
A southern hemisphere cyclone structure. The top diagram represents an eagle's view, the middle diagram is a cross-section of cloud and atmospheric motion, while the bottom diagram represents the pressure and wind structure across the cyclone.

Cloud

Satellite and radar imagery of tropical cyclones show that they are made up of an approximately circular mass of cloud with a cloud and precipitation minimum in the centre. The cloud mass is made up of thick stratiform cloud with embedded convective cells of cumulonimbus and cumulus forming long narrow bands spiralling towards the centre. The bands may be 20 to 40 kilometres wide and hundreds of kilometres long. In the southern hemisphere they spiral inwards in a clockwise direction, and in the northern hemisphere, anticlockwise. Meteorologists use satellite data to estimate the intensity of tropical cyclones (in the absence of aerial reconnaissance and surface observations). Cyclone intensity is related to the width of the spiral bands and the extent to which they wrap around the centre, the size and location of the eye within the central dense overcast cloud shield, and cloud top temperature differences between the eye and the surrounding cloud mass.

Surface winds

To be identified as a tropical cyclone, the winds must be at least 34 knots around the eye. As a cyclone develops, the area of gale-force winds expands outwards to 100 to 600 kilometres and can be highly asymmetric. The winds increase rapidly towards the center with the strongest winds occurring in a narrow band surrounding the eye. This region can be extremely turbulent and gusty. Maximum winds can reach 150 knots or more. The variation of wind and pressure at a location in the path of a storm centre is shown in Figure 14.23. The sharp dip at the centre is associated with the eye.

Central pressure

Central pressures in a tropical cyclone are usually below 1000 hPa. One of the lowest surface pressures ever recorded was 870 hPa in Typhoon Tip that occurred in the northwest Pacific Ocean in October 1979. Pressures decrease with increasing rapidity towards the centre with pressure gradients reaching one to two hectopascal per kilometre.

The eye

The eye is an area of relatively calm conditions. Normally it is a region of clear sky or scattered low cloud with light winds and no rain. The eye is sharply delineated from the surrounding areas of stronger wind, rain, and heavy cloud. It can range in size from 10 to 100 km (average 30 km) in diameter, usually decreasing as the strength of the cyclone increases. It is surrounded by a ring 10 to 40 km wide of heavy cloud (the eye wall) in which is embedded the strongest winds and heaviest rain. Severe turbulence in the eye wall, particularly at low levels, is extremely dangerous to aircraft.

14.32 Tropical Cyclone Life Cycle And Movement

Formative stage

A tropical cyclone usually develops in a pre-existing low-pressure trough over warm ocean water where the sea surface temperature exceeds 26°C. The wind shear between the lower and upper atmosphere is low, and there is an abundant supply of atmospheric moisture for vigorous convective cloud growth. The system becomes more circular, the pressure in the centre decreases and winds increase. Figure 14.24 depicts the stages of tropical cyclone development.

Immature stage

The pressure falls below 1000 hPa and winds increase to 34 knots. The convective clouds form into spirals and the eye develops. Continued development can result in the pressure falling below 970 hPa and winds exceeding 63 knots. The diameter of the storm may increase while the eye contracts as the storm strengthens.

Mature stage

At this stage the cyclone is at its maximum size and strength and the central pressure is steady. There may be fluctuations in eye diameter as the eye wall expands and contracts due to internal forces.

Decaying stage

When a cyclone has its energy supply interrupted, by moving over colder water or over land, it reaches the decaying stage. The system may persist over land as a rain-bearing depression or move into higher latitudes and interact with frontal systems. It may move into a region of increasing wind shear that disturbs the vertical alignment of the system causing the upper and lower circulations to become separated.

Movement

Tropical cyclones develop in the tropics equatorward of the subtropical ridge. They usually follow a path to the west, diverging from the equator then tracking more poleward before being caught up in the westerlies of the mid latitudes. In some cases, they may initially travel eastwards or even follow a looping track. Movement in any direction is possible. Speed of travel in the tropics is usually slow and increases towards higher latitudes.

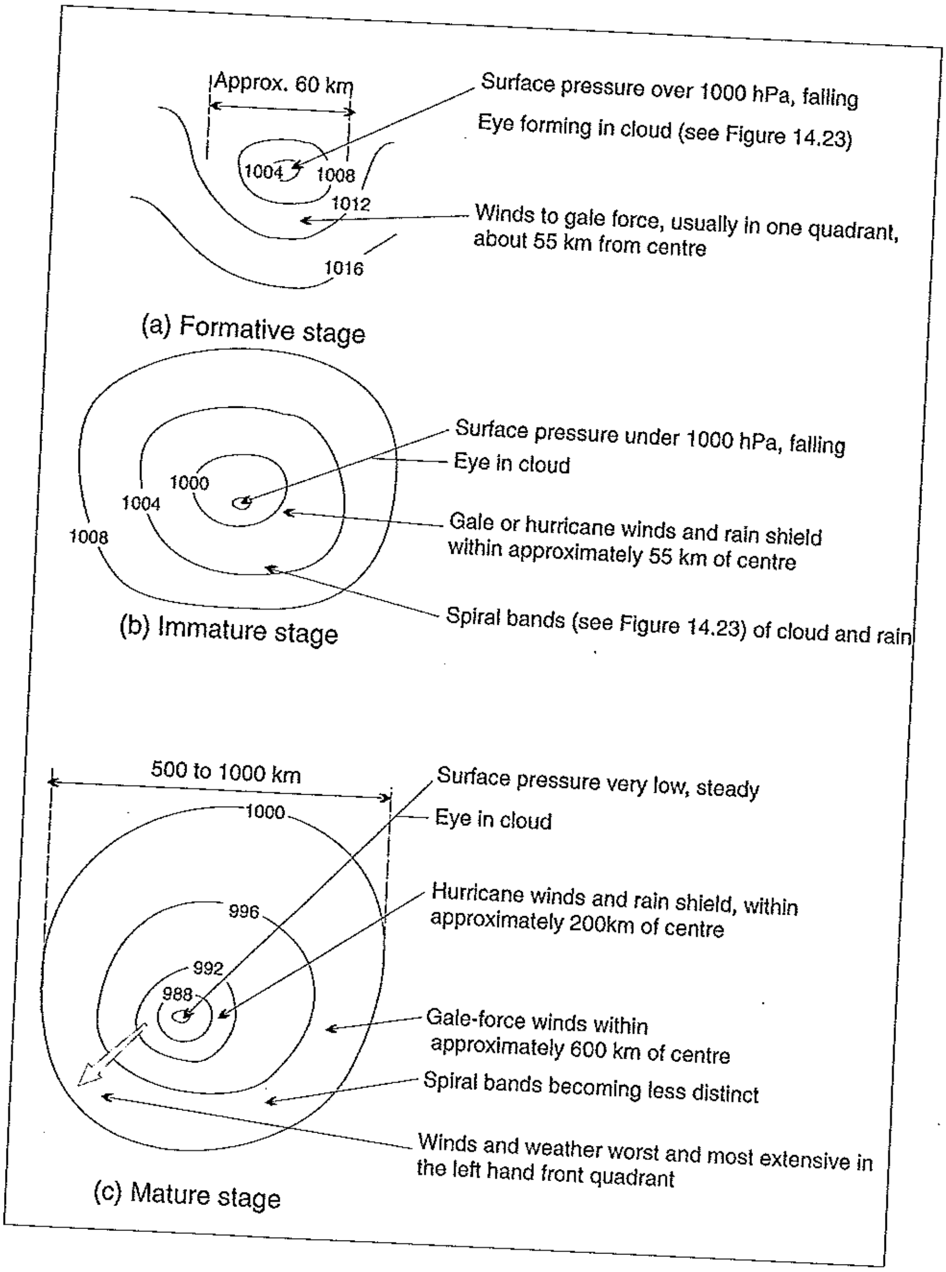


Figure 14.24
Stages of tropical cyclone development.

SATELLITE IMAGERY

Meteorological satellite imaging equipment views large segments of the earth and its oceans enabling measurements of numerous atmospheric parameters, including cloud formations.

There are two main types of meteorological satellite:

- geostationary (has an orbital speed equal to the earth's rotation, so that it remains at the same position above the equator);
- polar-orbiting (they orbit the earth in a north/south direction).

Satellites are able to produce several types of cloud images, the main two being visible (VIS) and infrared (IR) images that are available on the Bureau of Meteorology web page at (http://www.bom.gov.au).

Although satellite images can be displayed in colour, the following discussion focuses on black and white images, as it is these images that are provided to the aviation industry by the Bureau for flight planning purposes.

15.1 VISIBLE IMAGES

Visible images are similar to those taken by a standard camera with black and white film. They measure sunlight reflected by the earth's surface, clouds, smoke or other reflecting surfaces. When the sun is not shining on the earth the image or part thereof is black or very dark and clouds cannot be seen.

The grey-scale of visible images differentiates between levels of reflectivity as depicted in Figure 15.3. The brightest and most reflective surfaces (ice, snow, thick cloud tops) are in white shades, and the least reflective surfaces (oceans and earth) appear in grey/black shades. In general clouds are seen as white objects against the darker background of the earth's surface.

Very thin clouds can be transparent to visible light and thus exhibit weak reflectivity. They are often barely discernable.

Small clouds may not be detected if their size is below the resolution of the satellite (usually around one kilometre for visible images).

Texture (apparent roughness) displayed by the upper surfaces of clouds on visible imagery results from variations in cloud thickness and shadow. Shadows and highlights are characteristic features of visible cloud imagery giving it a three-dimensional appearance; this appearance is completely lacking in IR imagery. In unstable air, the tops of some convective clouds are often higher than others. Early in the morning and late in the evening when the sun angle is low, the higher tops cast small shadows on the cloud layers at lower levels.

15.2 INFRARED IMAGES

Infrared images depict heat radiation emitted by objects at the infrared wavelengths, beyond the red part of the spectrum, and around 11 microns. They display the temperatures of cloud tops or the earth's surface. If there are several layers of cloud at a location then the temperature displayed is of the highest and coldest cloud as depicted in Figure 15.2. Cold cloud tops (-30°C or colder) appear white. The earth's surface (+30°C or warmer) appears black. Temperatures in between -30°C and +30°C are shown in shades of grey.

For infrared images the brightness, or the whiteness, of the image is purely dependent on the infrared radiation from surfaces, i.e. it depends on the temperature of the radiating surface.

The resolution for infrared images is less than that for visible images, and is usually five kilometres.

15.3 CONCURRENT VIEWING OF INFRARED AND VISIBLE IMAGES

Concurrent viewing of infrared and visible images helps determine the make-up of significant cloud formations and weather features such as frontal regions, thunderstorms, cyclones, low cloud and areas where no cloud exists (see Figures 15.1 and 15.2). Images can also show areas of dust, smoke and volcanic ash. Although images do not show turbulence per se they can show clouds associated with turbulence, i.e.

Table 15.1
Cloud types and satellite image signatures.

Cloud Type	FORM	TONE: Visible images	TONE: Infrared images
Cumulus Cu	Small elements or groups of elements. If Cu elements are below sensor resolution, land or ocean areas appear mottled or slightly brighter than if cloud free.	Medium brightness.	Dark tone; usually difficult to detect
Stratocumulus Sc	Closed cell pattern (VIS imagery) over oceans in areas of cold air advection. Cell size varies depending on inversion height. Gravity waves often present when viewed in motion. Mountain wave small lee vortex patterns may be present in clouds.	Centre of cells in pattern bright, become grey toward the edges where cloud thins. If cells are below sensor resolution they may appear smooth, as if stratus.	Surface uniform dark grey; cellular structure not evident. Can be difficult to detect when cloud tops are low, and close to ground temperature.
Cumulus Cu (grouped)	Irregular shaped elements or groups of elements. Frequently organised into lines or open cellular patterns in areas of cold air advection over oceans.	Bright.	Relatively bright; depends on coldness of cloud top.
Cumulonimbus Cb	Globular or carrot shaped depending on vertical wind shear. Wind shear: upwind edge sharp: opposite down wind, anvil edge indistinct.	Very bright: distinct shadows and highlights when sun angle low.	Bright white in centre or adjacent to upwind boundary of anvil. Darker toward downwind edge.
Fog & Stratus Fg & St	Smooth tops: boundaries often sharp and defined by topography.	Uniform medium grey tone if thick: mottled if thin.	Uniform dark grey shade: varies with season. Difficult to detect since temperature is usually close to surrounding land or sea temperature; can appear darker than surrounding land at night.
Altostratus & Altocumulus As & Ac	Smooth tops, boundaries can be ragged or smooth, often in layers. When in combination with deep convection, tops appear bumpy if sun angle is low. Cellular structure of Ac too small for sensors to resolve and therefore cannot be distinguished from As. Gravity waves common when layers thin.	Light grey; appears mottled or striated depending on thickness or layered structure.	Uniform medium grey tone; depends on height. Can appear darker than surrounding snow-covered land in polar regions.
Cirrus Ci	Banded fibrous structure 50 - 100 km in width. Features of underlying terrain and cumulus clouds are sometimes detectable through clouds.	Dark grey to grey tone depending on underlying surface.	Light grey in tone. Fibrous structure not as evident as in VIS.
Cirrocumulus Cc	Cloud elements formed by thick dense convective cirrus, cloud elements often are globular or elongated and often have detectable shadows.	Light grey to white.	White tone.
Anvil Cirrus Ci or Cs	Smooth textured except where overshooting tops cast shadows. Sharp distinct upwind edge to plumes. Downwind edge filmy, fibrous and indistinct.	Brightest over generating cell with decreasing brightness downwind.	Brightest over generating cell with decreasing brightness downwind.
Cirrostratus Cs	Generally smooth and uniform tops but sometimes fibrous in appearance. May be in long bands or an extensive sheet.	Appears light grey when thin and whiter as thickness increases.	Varies from white to grey. Difficult to distinguish from middle level clouds.

mountain wave clouds and therefore can indicate turbulent regions (see Chapter 10).

On satellite images.

- High, thick clouds are white on both visible and infrared images because they are very cold and reflect sunlight strongly.
- Low cloud is difficult to detect in infrared images because there is little contrast between the temperature of the earth and the cloud top. Low-stratus cloud and fog are particularly difficult to detect in infrared images. However daytime visible images show low cloud and fog very clearly because both phenomena are highly reflective. Ocean areas vary in temperature so on IR images the oceans appear as shades of grey whereas on VIS images ocean areas are uniformly dark (except for sun glint);
- High and low layers—VIS images can show shadows and highlights while IR images reveal the temperature differences of different layers;
- Cloud texture is the degree of apparent roughnesss displayed on the upper surfaces in the VIS image. It is due largely to shadow. Clouds with a smooth surface are usually stratiform. Mottled appearance may be due to variable thickness as in stratocumulus. Uneven or bumpy cloud tops usually indicate cumuliform cloud;

1. Oceans are black in the VIS and shades of grey in the IR.
2. Land surfaces are black or very dark in the IR and lighter shades of grey in the VIS.
3. The VIS clouds have texture while the IR has a flatter appearance.
4. Brightness or whiteness is about the same for IR and VIS for high cloud associated with the tropical cyclone and tops of thunderstorm clouds in the north and over the Tasman Sea.
5. Low cloud south of the continent appears dull grey in the IR but bright and speckled in the VIS, indicative of small cumulus or stratocumulus cloud.
6. Middle level cloud Ac and As) in the vicinity of the tropical cyclone appears in mid shades (relatively warm) in the IR and bright in the VIS.

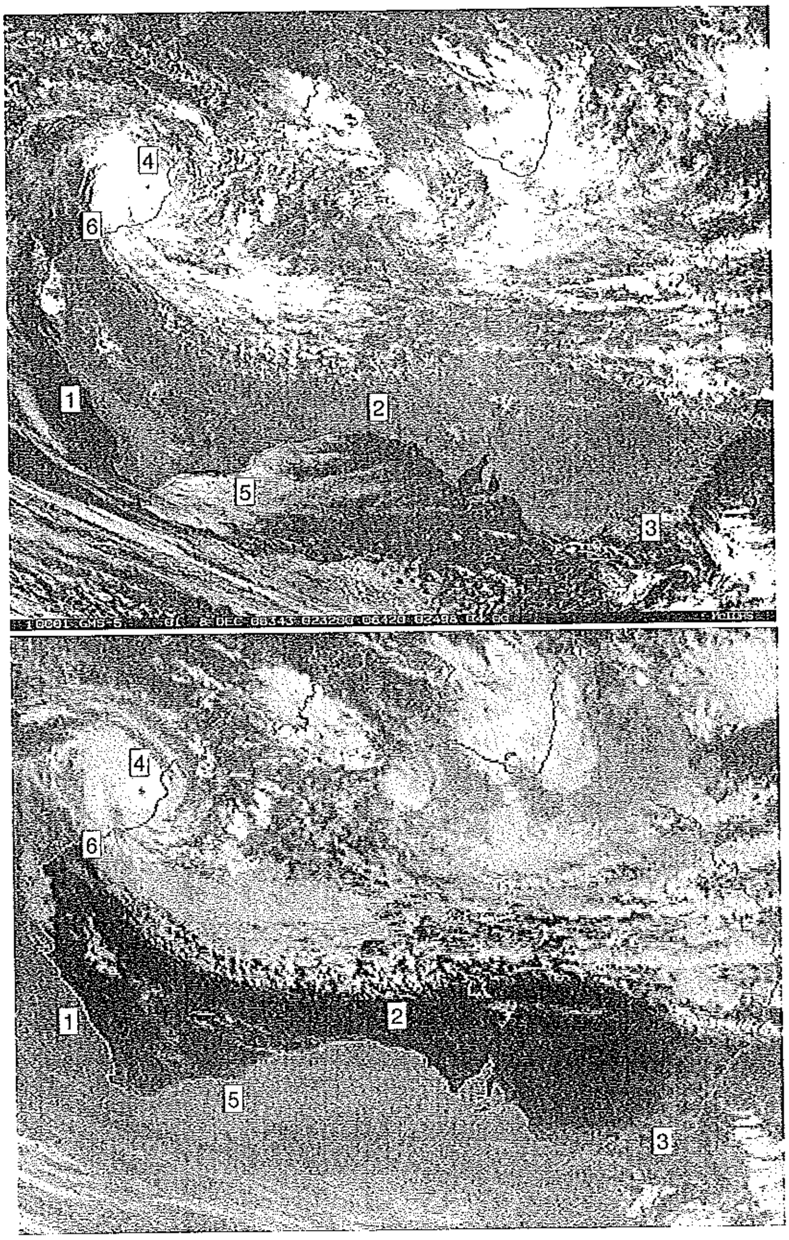


Figure 15.1
Visible and infrared images for the same time for 8 December 2000.

- the fibrous texture of cirrus also shows up on IR images, but otherwise cloud texture is usually not a characteristic of IR imagery.

Certain features only become apparent by animating a sequence of images. This technique is invaluable for the interpretation of many weather features (e.g. movement and development of fronts or genesis of tropical cyclones) as well as differentiating between cloud and ground.

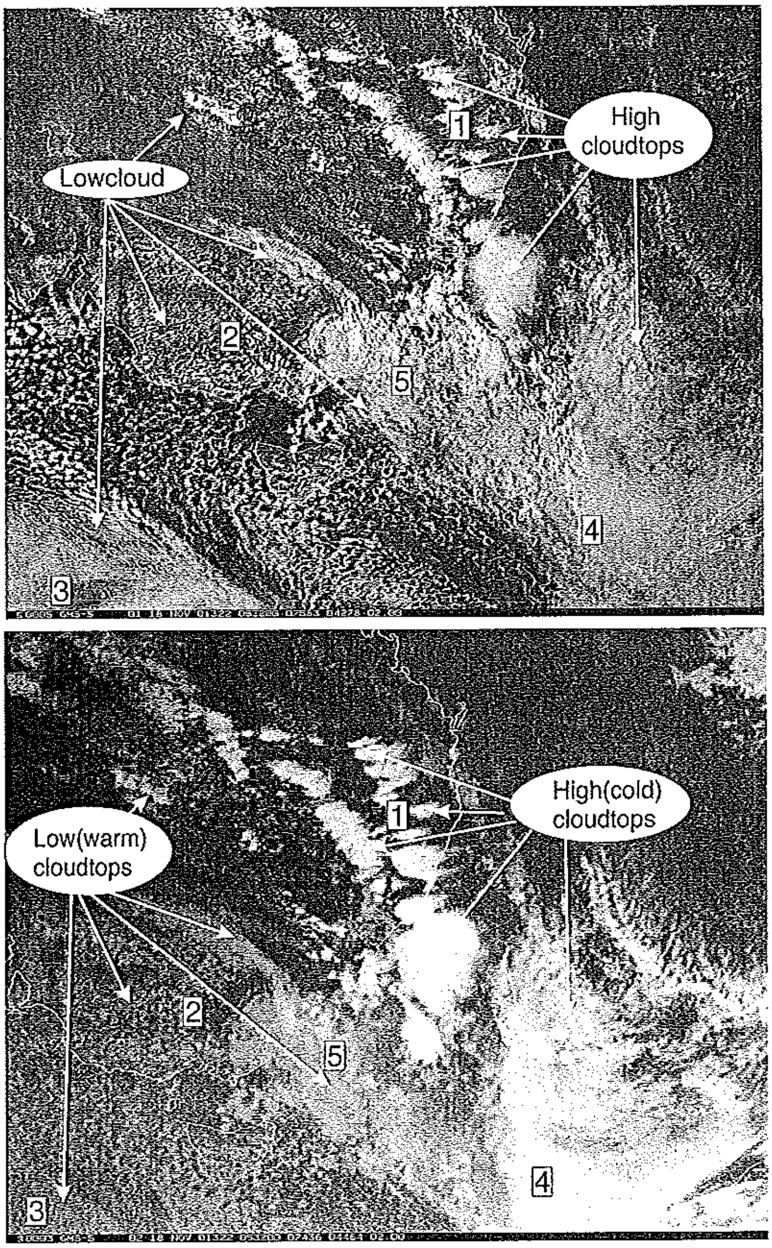
When using satellite imagery, the viewer must remember that the satellite sensors typically only sense the top feature, e.g. the top of clouds. Apparent inconsistencies can occur when the images are compared with actual observations. If a cloud layer is stable in its lower levels and unstable aloft, for example, a surface observer will report a stratiform cloud type, while the imagery shows cumuliform.

Table 15.1 sets out general criteria for identifying cloud type based on image tone and structure.

The following two satellite images in Figures 15.1 depict the difference in appearance between VIS (top) and IR (bottom) images taken in the early afternoon in summer.

Further examples of the difference between infrared and visible satellite images (taken on a late spring afternoon) are shown in Figure 15.2.

15.2
VIS and IR image with lower cloud types in the southwest sector and high cumulonimbus clouds and active thunderstorm in the northwest sector.



An overview of the images

Both images show bright white tops of cumulonimbus clouds (anvils) forming along the trough.

1. Anvil cirrus is usually seen as bright white, often in a carrot shape.
2. Cumulus cloud behind the front in the colder southerly wind stream south of Australia appears as a field of many irregularly shaped cells of various sizes.
3. Stratocumulus cloud in the southwest corner of the images appears as patches (due to white near the centres, and light grey near the edge, where the cloud is thinner), producing a pebbly or honeycomb appearance. On IR, Sc is medium to dark grey. If breaks in the Sc layer are very small, appearance will be continuous uniform grey.
4. Altostratus cloud (thick) in the southeast corner of the images is displayed in the VIS as dull white with a fairly uniform surface. In the IR As appears mid white.
5. It is difficult to determine the make-up of the cloud adjacent to the southeast coast even when comparing the IR and VIS images. It appears to be mainly thin altostratus with patches of altocumulus. Ground observations from the area indicated altostratus overlying stratocumulus and low stratus. Rain was tending to showers at the time of the images.

WEATHER WATCH RADAR

The Bureau of Meteorology operates a number of dedicated weather watch radars around Australia. These are supplemented by part-time wind-finding radars, which have routine periods when weather watch coverage is not available. A selection of images from these radars is freely available on the Bureau of Meteorology web site, http://www.bom.gov.au.

The images are useful in determining precipitation areas, type and strength of precipitation, whether there are showers, thunderstorms, hail, general rain or frontal systems moving across an area.

Sequences of images (looped images) indicate the position and rate of movement of frontal systems or individual precipitation cells.

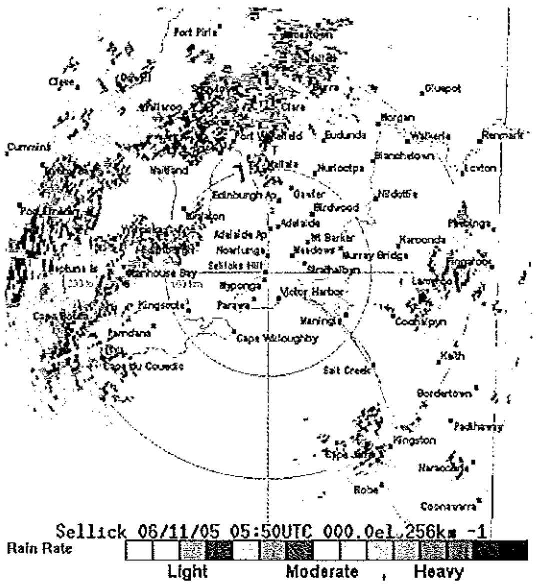


Figure 16.1
A typical Australian Bureau of Meteorology radar display. In this example the radar has detected rainfall rates varying from light to moderate.

16.1 How Weather Watch Radar Works

RADAR (RAdio Detection And Ranging) is a system whereby pulses of radio waves are transmitted by an antenna in a highly focused beam and are reflected off targets and returned to a receiver via the same antenna. For weather watch radar, the targets are precipitation (rain, hail, snow or drizzle). The radar attempts to locate all areas of rain within range of the antenna by sweeping the radar beam just above horizontal. The radar's computer determines the direction of the precipitation from the antenna, and the distance to the precipitation from the time taken for the radar signal to return to the receiver. Not only is the location of the precipitation determined, but also the 'reflecting power' of the rainfall (which depends on the size of the raindrops and their concentration) is calculated, thus providing an estimate of rainfall intensity. In summary, the display produced by the radar's computer gives a horizontal map of the location of rain and an estimate of how heavily it is falling. Note that the radar does not 'see' clouds but the rainfall those clouds produce. These areas of precipitation, which the radar 'sees', are often called radar echoes because the radar beam reflects off them.

The radar display shows a topographic base map of the area surrounding the radar site with the coastline, major rivers and town names and with range rings at 50 kilometre spacing. A colour bar at the base of the image shows rainfall intensity levels. The radar echo intensity level provides an approximate indication of rainfall rate. The following values can be used as a general guide but they are not always accurate.

Level	Colour	Approx. Rainfall Intensity (mm/hr)
0	clear Not visible	Under 0.2
1	Off-white	0.5
2	Sky-blue	1.5
3	Light Blue	2.5
4	Blue	4
5	Light Cyan	6
6	Cyan	10
7	Dark Cyan	15
8	Yellow	20
9	Yellow-orange	35
10	Orange	50
11	Orange-red	80
12	Red	120
13	Dark Red	200
14	Maroon	300
15	Dark Brown	over 360

Above the intensity indicator - the location, range and time (UTC) to the nearest 10 minutes of the image is given. Below the intensity indicator - the actual time of the image transmission is given in UTC along with local EST, CST and WST.

16.2 Limitations Of Radar Interpretation

The following important points should be taken into account when interpreting radar images:

- The intensity of echoes tends to decrease with increasing distance from the radar. This is because;

  - the radar beam broadens with distance, thus decreasing the proportion of the beam which is filled with rain, which reduces the echo intensity;

  - the radar beam becomes further from the ground with distance (partly because of the earth's curvature), thereby missing the lower parts of any rain;

  - the beam can lose power when passing through heavy rain, thus reducing the echo intensity further out from the radar.

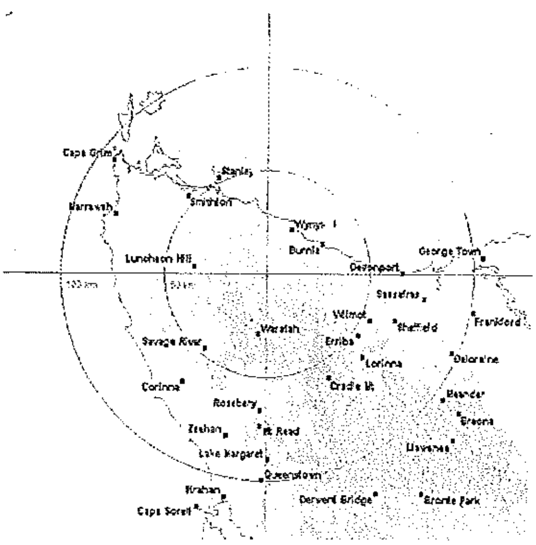


Figure 16.2
Rough sea (sea waves) depicted as precipitation echoes.

- The presence of significant echoes at long range probably indicates the presence of large amounts of rain at high levels above the ground (e.g. a thunderstorm).
- The presence of obstructions (permanent echoes) such as mountains and buildings, within the range of the radar can block the radar beam, thus significantly reducing the echo intensity from rain on the other side of the obstruction.
- The radar may sometimes show echoes from non-precipitation targets such as aircraft, large fires, swarms of insects, flocks of birds or the land or sea surface. Surface echoes may be particularly noticeable when unusual atmospheric conditions bend the radar beam back down to the surface, or when high winds cause rough seas as depicted in Figure 16.2.
- The radar images seen on the web are actually composites derived from a number of successive rotations (scans) of the radar antenna, each at a slightly higher elevation angle. The image is made up of a number of concentric bands, with echoes at short ranges being derived from high-angle antenna scans and longer-range echoes coming from the lower elevation angles. As a general rule, the elevation angles and the range boundaries between the concentric bands are chosen to give an area of coverage broadly centred on about 10 000 feet altitude. In practice, the vertical extent of the coverage will increase with distance due to the antenna beam width (e.g. two degrees) while earth curvature effects at longer ranges will further modify its shape. While the settings are chosen for the best all-round compromise, there will

be occasions when precipitation echoes whose altitude is above or below the radar's vertical coverage will not be seen at all, or may be displayed at reduced strength.

- The intensity of drizzle may be underestimated because of the small droplets or because the precipitation is actually below the radar beam.
- Virga, or rain not reaching the ground, at a distance from the radar will return light echoes indicating rainfall in the area when in fact the rain is not reaching the surface.
- Occasionally, solar interference creates false radial images as depicted in Figure 16.3.
- Other radars may interfere, resulting in images similar to those depicted in Figure 16.4.
- On occasions a relatively thick film of water may flow over the radar dome reducing beam efficiency and reflectivity levels. Very heavy rain and hail directly falling over the radar dome can greatly reduce the effectiveness of the radar as is indicated by the acute attenuation depicted in Figure 16.5. The images are only one minute apart but the second image was taken with severe rain and/or hail falling over the radar dome. At this time the radar cannot 'see' surrounding storm activity. The example highlights

Figure 16.3
Solar interference with telltale cone pattern.

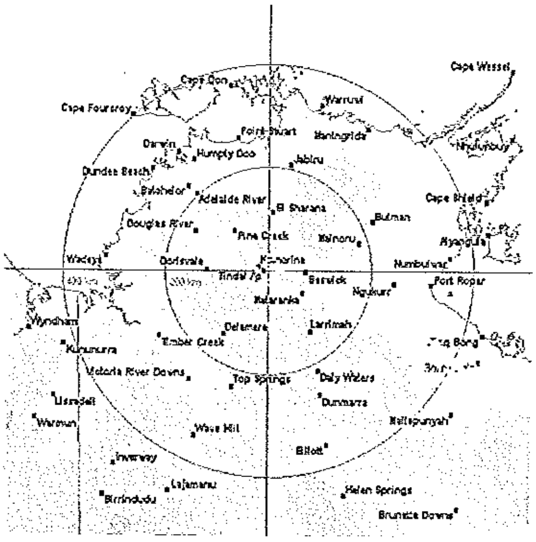


Figure 16.4
Radar interference.

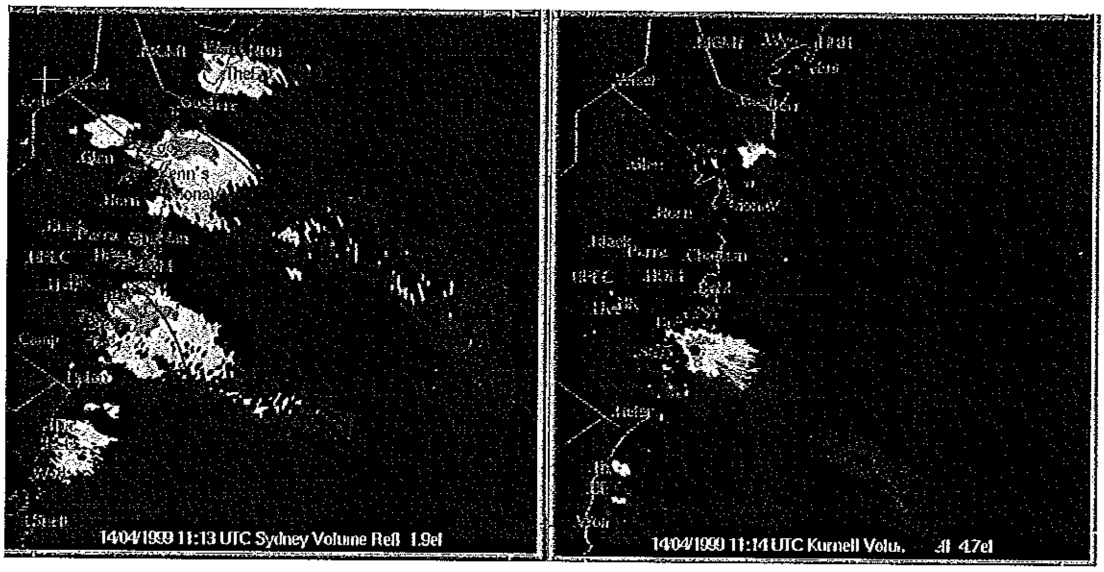


Figure 16.5
Radar images one minute apart showing acute attenuation of echoes due to very heavy rain and/or hail falling over the radar dome. Note: these images, although different from those available on the web site, are indicative of the problem of acute attenuation.

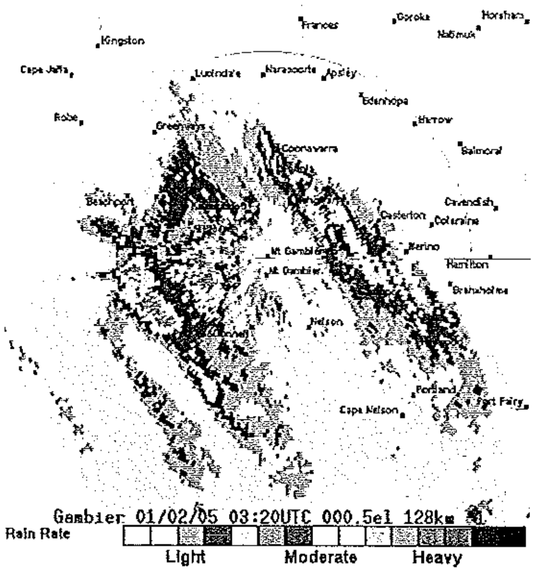


Figure 16.6
Extensive areas of light to moderate rain.

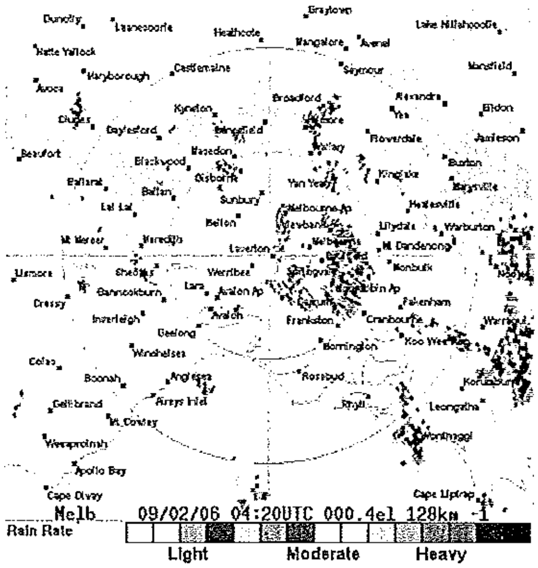


Figure 16.7
Light to heavy showers.

the importance of viewing a sequence of radar images.

16.3 Radar Features To Watch For

Rain Bands

Radar echoes from widespread rain are usually extensive and fairly uniform in intensity.

The estimated rainfall intensity usually appears as light to moderate because of the smaller raindrop size produced in such rain-bands as depicted in Figure 16.6. Because of the extensive rain echoes, the range of the radar echoes may be reduced.

Showers from Cumulus Clouds

Radar echoes from showers falling from cumulus clouds appear as sharp-edged cells on the radar display as depicted in Figure 16.7.

Heavy Precipitation from Thunderstorms

Radar echoes from the rain and hail produced in thunderstorms have very sharp-edged cells with intense cores indicating heavy rainfall.

Very heavy rainfall with hail is depicted in Figures 16.5 and 16.8. The rainfall rates exceed 100 mm per hour. Rainfall rates of such high intensity are indicative of severe storm activity.

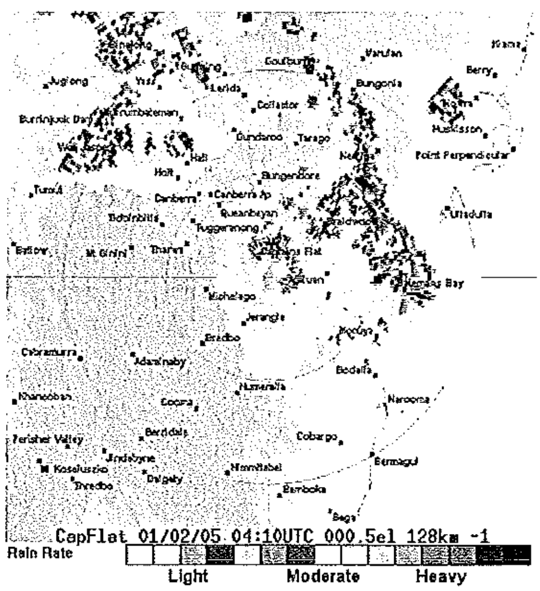


Figure 16.8
Severe thunderstorms to the north of Batemans Bay associated with large hail, damaging winds and heavy rain.

Thunderstorm precipitation cells can appear as isolated cells or in clusters or lines. Each cell tends to last for 30 minutes or more. Fast moving cells, rapidly growing cells, a bow in the direction of movement of a line of cells and/or a long-lived cell moving in a markedly different direction to others may indicate the potential for severe weather (large hail, damaging winds and/or very heavy rain). Also, a very slow moving cell or the repeated passage of a number of cells over a particular location could indicate potential for flash-flooding.

Figure 16.9 shows a radar image of a severe thunderstorm. Note the tight colour gradient indicative of very strong updrafts and heavy falls of rain and hail. See also the large solid anvil indicating a very well-developed storm in Figure 16.10.

Tropical Cyclones

Tropical cyclones produce widespread heavy rain. The tendency for the rain bands, often with embedded cells, to spiral around the rain-free cyclone 'eye' produces a characteristic radar pattern (Figure 16.11). Identification of the 'eye' is very useful in monitoring the rate and direction of movement of the tropical cyclone. An IR satellite image (three hours after radar image) is presented in Figure 16.12 (see Chapter 15 for interpretation).

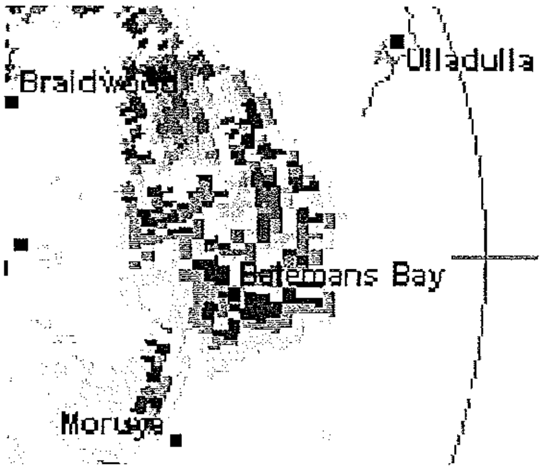


Figure 16.9
Thunderstorms with hail.

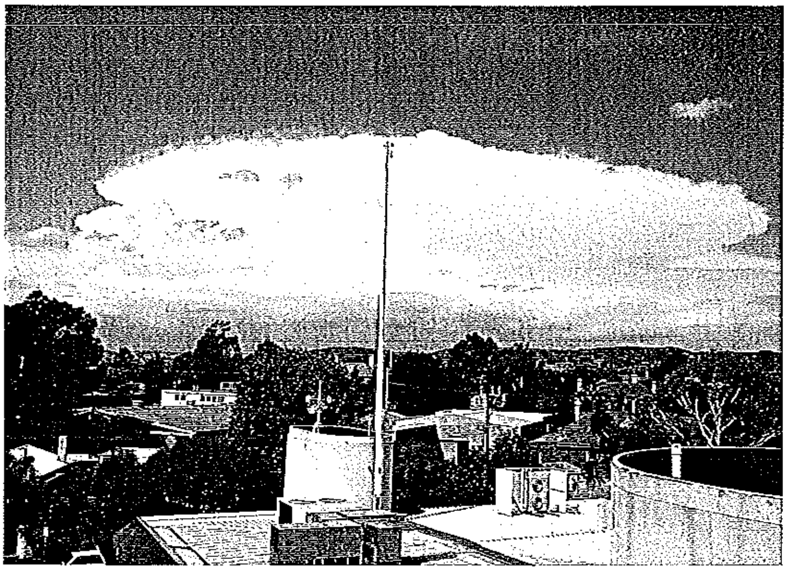


Figure 16.10
A cumulonimbus cloud typical of the type associated with severe storms and radar images similar to Figure 16.9.
Photo © Andrew Watson

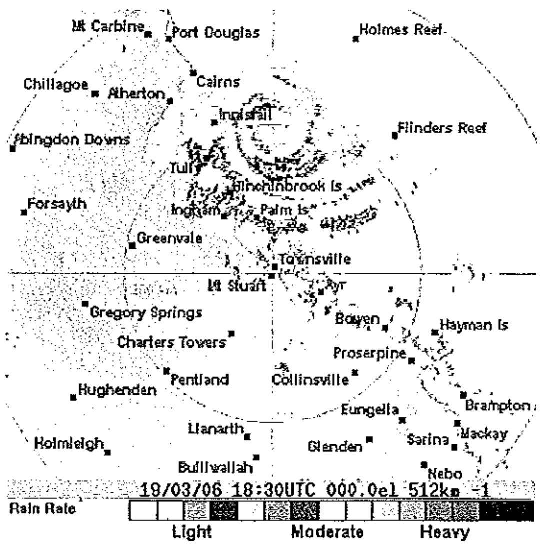


Figure 16.11
Severe tropical cyclone Larry 20/03/06, 4:30am AEST (19/03/06, 1830 UTC).

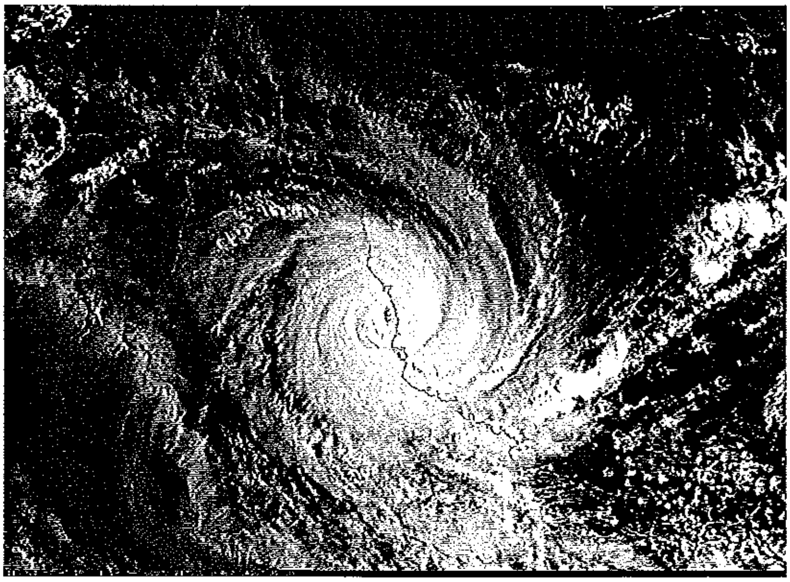


Figure 16.12
Severe tropical cyclone Larry - 20/03/06, 7:30am AEST (19/03/06, 2130UTC).

Figure 16.13
Location of Bureau of Meteorology radars, both weather watch and wind finding.

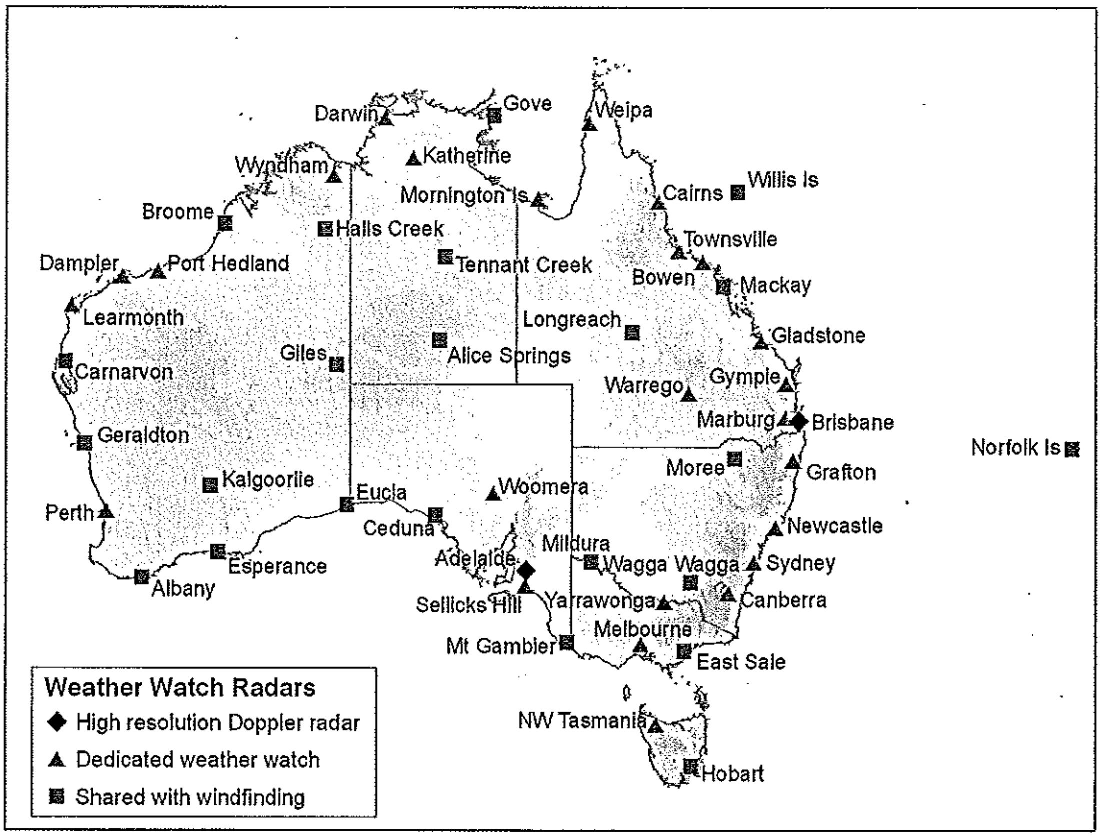


Table 1
Routine periods when weather watch coverage is not available.

UTC/GMT	05:15 - 06:45	11:15 - 12:45	17:15* - 18:45	23:15 - 00:45
Eastern Daylight Time	04:15 - 05:45pm	10:15 - 11:45pm	04:15 - 05:45am	10:15 - 11:45am
Eastern Standard Time	03:15 - 04:45pm	09:15 - 10:45pm	03:15 - 04:45am	09:15 - 10:45am
Central Daylight Time	03:45 - 05:15pm	09:45 - 11:15pm	03:45 - 05:15am	09:45 - 11:15am
Central Standard Time	02:45 - 04:15pm	08:45 - 10:15pm	02:45 - 04:15am	08:45 - 10:15am
Western Standard Time	01:15 - 02:45pm	07:15 - 08:45pm	*12:15 - 01:45am	07:15 - 08:45am

* Note that the 17:15UTC flight is performed one hour earlier in WA

16.4 Availability Of Radar Data

Radar images on the internet are normally updated every 10 minutes however, note that there are full and part-time radars as indicated in Figure 16.13.

Full-time Weather Watch Radar should be online at all times, with images updated approximately every 10 minutes, unless there are technical difficulties or scheduled maintenance.

Part-time Wind-finding Radar have routine periods when weather watch coverage is not available. This normally occurs, up to 4 times a day, for approximately 1.5 hours as shown in Table 1. During these periods these radars will be engaged in tracking of high-level balloons for the measurement of winds in the upper atmosphere.

VOLCANIC ASH

Volcanic ash is hazardous to aircraft; its effects range from a peculiar odour in the cabin to engine failure. The volcanic ash and corrosive gases from an erupting volcano can cover a wide area and remain in the atmosphere for days.

Volcanic ash is composed of pulverised rock, predominantly silica (in the form of tiny glass shards) in most cases. It is usually electrically charged resulting in lightning, and is accompanied by corrosive gases such as hydrochloric acid and sulphur dioxide, which over time converts into droplets of sulphuric acid.

The first significant aviation encounter with volcanic ash occurred in June 1982. A British Airways 747, flying over Indonesia at night, encountered ash from Mt Galunggung, lost power in all four engines and suffered severe damage (including windscreen abrasion that severely restricted visibility). The aircraft descended to 12 000 feet before the crew was able to restart some engines and make an emergency landing in Jakarta. Three weeks later a similar incident happened involving a Singapore Airlines 747, which lost power in two engines. It also made an emergency landing.

While it was known that aircraft had experienced problems with ash in the past these problems had been restricted to abrasion of cockpit windows and blockage of pitot-static tubes. The June 1982 incident alerted the aviation industry to the possibility that volcanic ash clouds have the potential to cause a major accident. Figure 17.1 shows eruptions and ash cloud that have resulted in over 30 aircraft encounters with volcanic cloud since 1982, and have cost millions of dollars in damage and diversion costs.

17.1 Effect Of Ash On Aircraft

The most critical effect of volcanic ash on aeroplanes is engine damage. The heat of the engine can cause the silica in the ash to melt and fuse into a glass-like coating on components further back in the engine, causing loss of thrust and possible flameout. In addition volcanic ash can abrade engine

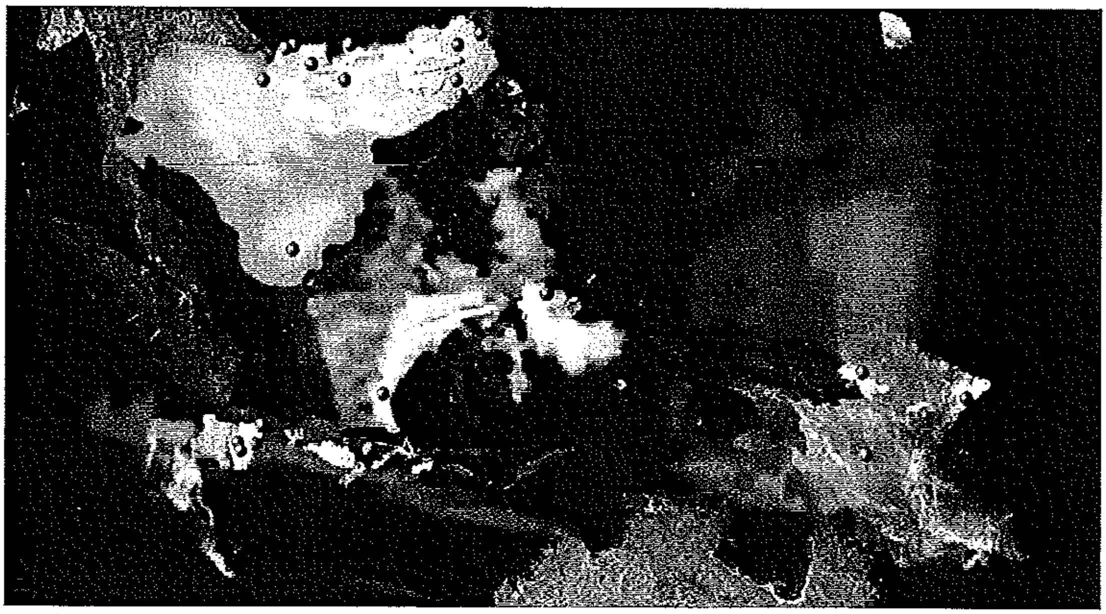


Figure 17.1
Mosaic of volcanic ash clouds from satellite imagery and space shuttle photos, 1979 - 2001 with encounters since 1982 depicted by red dots. Note: not all encounters are shown in Figure 17.1, exact locations are unknown for some incidents and it is probable that many minor incidents go unreported.

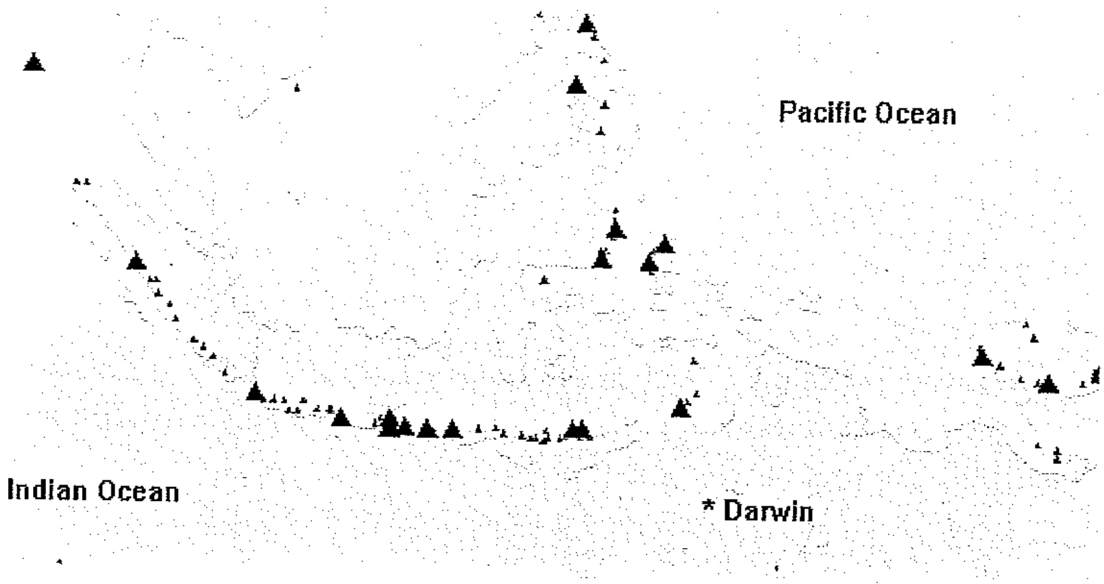


Figure 17.2
Locations of active volcanoes (that have erupted since 1900) depicted as triangles; the larger triangles are volcanoes for which the Darwin VAAC has issued volcanic ash advisories since it was established in February 1993.

parts and contaminate electrical systems, avionics equipment, hydraulic systems and fuel.

A pilot approaching an ash cloud may not be able to distinguish the ash from other clouds such as cumulonimbus. Indications that an aircraft has entered a volcanic ash cloud include the appearance of smoke or dust in the cockpit, and fine ash collecting on flat surfaces. Pilots have reported an acrid odour similar to electrical smoke and the smell of sulphur. Outside the cabin, lightning and St. Elmo's Fire may be observed around the aircraft along with a bright orange glow around jet engine inlets, torching from the tailpipe, and flameouts. The windscreen can become eroded and opaque very rapidly and there is a likelihood of electrical equipment overheating and warning lights coming on. There have been incidents when volcanic ash has activated cargo fire warning systems.

Even with very small concentrations of airborne volcanic ash gradual deterioration of aircraft components will occur over time. Small volcanic ash particles can remain suspended in the atmosphere for many days after an eruption.

17.2 International Airways Volcano Watch (IAVW)

In response to the incidents over Indonesia, a major international effort has been underway to track volcanic ash clouds and warn aircraft.

The International Civil Aviation Organization (ICAO) took the lead in implementing the International Airways Volcano Watch (IAVW). This involved the establishment of nine Volcanic Ash Advisory Centres (VAAC), as well as recommended practices and procedures covering the observing and reporting of volcanic activity and ash clouds, the issuance to aircraft of warnings and, as necessary, information regarding the closure of air routes. The Bureau of Meteorology operates one of the VAACs in Darwin. The other VAACs are located at Anchorage, Buenos Aires, London, Montreal, Tokyo, Toulouse, Washington and Wellington.

VAACs use satellite detection techniques, combined with ground reports from volcanological agencies, pilot reports via special AIREPs, meteorological knowledge and numerical models to track and forecast the movement of volcanic ash clouds. When volcanic ash clouds are detected within the area of responsibility of the Darwin VAAC, an area that extends to 10 degrees north covering Indonesia, Papua New Guinea and parts of the Philippines, the VAAC issues a volcanic ash advisory. Volcanic ash advisories are distributed to meteorological watch offices, air traffic control authorities, and the operations centres of major airlines in the region.

Many volcanoes to the north and east of Australia are active (depicted in Figure 17.2).

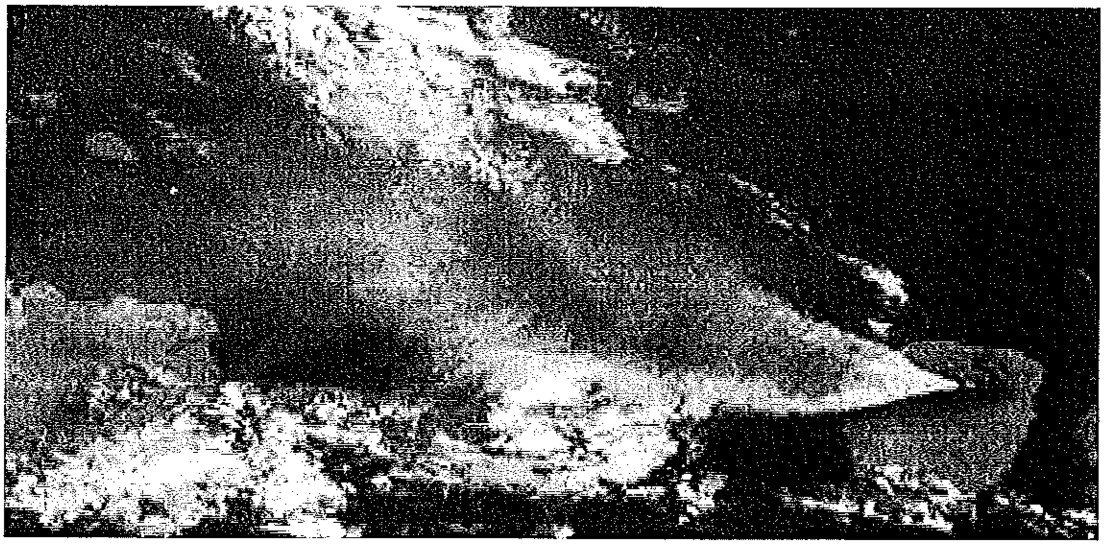


Figure 17.3
Volcanic ash cloud streaming to the west, from Mount Rinjani.

The Darwin VAAC which issues volcanic ash cloud advices as detailed in Chapter 18 monitors these volcanoes.

17.3 Detecting Volcanic Ash

It is critical to understand that aircraft radar and meteorological weather watch radar, will not detect volcanic ash. Thus visual pilot reports are extremely important.

Although enhanced satellite imagery can be used to track volcanic ash plumes, it can be difficult to distinguish between volcanic ash clouds and water/ice clouds such as cumulonimbus. The example given in Figure 17.3 shows some cloud and the ash plume from Mt Rinjani on the island of Lombok, Indonesia, from an eruption on 2 July 1994. The ash plume can be clearly seen stretching from Lombok west across the island of Bali. This eruption had a major impact on the heavily used airspace north of Australia.

An ash plume from an eruption at Rabual, Papua New Guinea is shown in Figure 17.4.

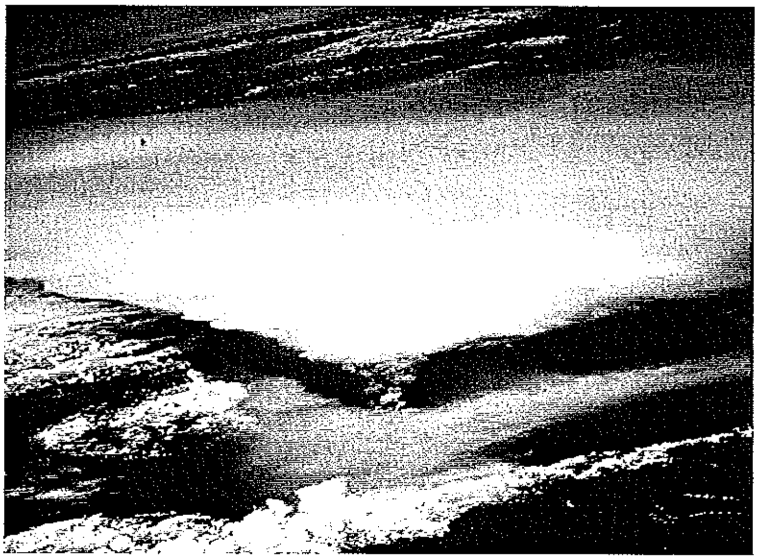


Figure 17.4
Volcanic cloud rising before spreading out from an eruption at Rabual, Papua New Guinea on 19 September 1994. This photo shows the large white billowing eruption plume is carried in a westerly direction by the weak prevailing winds. At the base of the eruption column is a layer of yellow-brown ash being distributed by lower level winds. A sharp boundary moving outward from the centre of the eruption in the lower cloud is a pulse of laterally-moving ash which results from a volcanic explosion. Picture taken from Space Shuttle Discovery. (Image courtesy of NASA).

Ash cloud can remain in the atmosphere at dangerous concentrations for several days until the particles gradually disperse and eventually fall out under the influence of gravity. During this time ash clouds can travel thousands of kilometers. After the eruption of Cerro Hudson in Chile on the 15 August 1991, ash cloud circled the southern hemisphere and was detected five days later over southern Australia as depicted in Figure 17.5.

17.4 More Information

More comprehensive information on volcanic ash, the IAVW and recommended general procedures to mitigate the effect of volcanic ash is available in ICAO Document 9691 Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds, and ICAO document 9766, Handbook on the International Airways Volcano Watch.

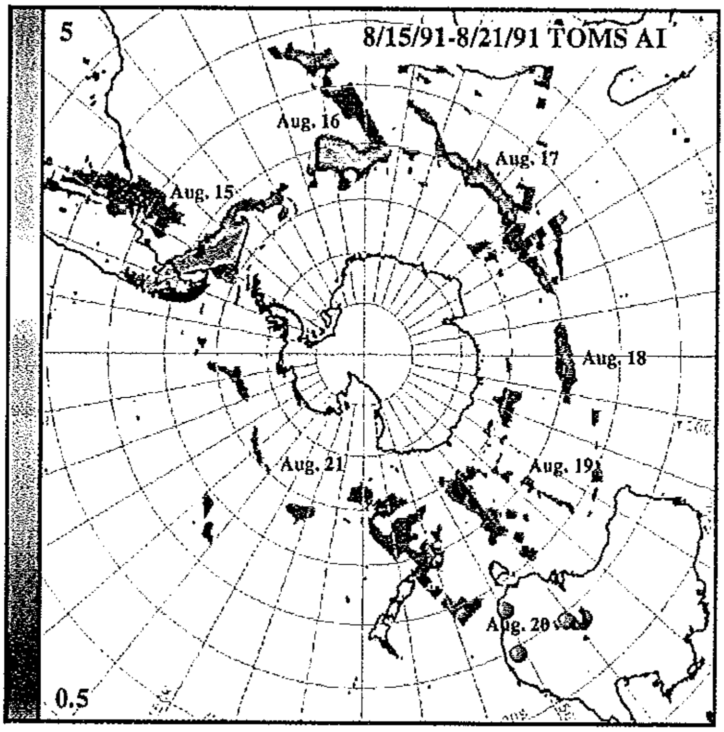


Figure 17.5
Ash cloud from the eruption of Cerro Hudson in 1991 in Chile is depicted over a six-day period. Some encounters over Australia are depicted by red dots.

METEOROLOGICAL SERVICES FOR AVIATION

The purpose of meteorological services to aviation is to provide aircraft operators with the meteorological information necessary for safe, regular and efficient air navigation and to support other aeronautical activities.

These services are provided within the technical and regulatory framework of the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO). In particular, the Convention on International Civil Aviation (the Chicago Convention) sets out uniform standards and practices in the provision of meteorological services to international aviation to which Australia, as a signatory to the convention, adheres. The Convention also requires that each signatory state designate a Meteorological Authority, which, in Australia's case, is the Bureau of Meteorology (the Bureau). While the Convention applies specifically to international aviation, its obligations are given effect in domestic law through a number of Acts of the Australian Parliament, including the Meteorology Act 1955 which describes the Bureau's function in supporting civil aviation, and the Civil Aviation Act 1988, under which the Civil Aviation Safety Authority (CASA) is the regulator of domestic civil aviation.

18.1 Meteorological Services to Aviation

Meteorological services to aviation include observations, forecasts, warnings and advice both in the vicinity of aerodromes and en-route, and specialised briefings and displays of meteorological conditions. These services are provided to aircraft operators, to search and rescue operations, and to Airservices Australia for use in air traffic management and for further dissemination to aircrew and other aeronautical units.

When a forecaster makes a prediction, the most probable conditions on the basis of the available information are described. The confidence the forecaster has in the prediction will depend on a number of factors such as the location, availability of observations, the season, the complexity of the particular situation, the elements being forecast and the period of the forecast. Elements, such as fog and low cloud are usually more difficult to predict with precision than others, such as upper wind and temperature.

Pilots who make the most effective use of weather services are usually those who understand forecast limitations. These pilots look upon forecasts as professional advice rather than categorical statements and take every opportunity to secure amendments and update their forecasts.

Amendments are usually not made unless expected changes from the original forecast are operationally significant, since there is a need to stress important amendments and eliminate unnecessary communication loads.

18.2 Availablilty Of Meteorological Information

The availability of meteorological information is set out in the Airservices Australia publication Aeronautical Information Publication (AIP) and the CASA publication VFR Flight Guide. Briefing services are available as indicated in these publications.

Information for flight planning purposes should be obtained through Airservices Australia at http://www.airservicesaustralia.com - click on Pilot Briefing Services.

Additional services such as radar, satellite images and a description of the Bureau's aviation weather products are available at http://www.bom.gov.au/.

GLOSSARY OF TERMS

ACCRETION
The process of supercooled water droplets freezing on impact with a snow-flake, ice particle or other cold object. Ice can accumulate on airframes by way of accretion

ADIABATIC COOLING
Cooling of a parcel of gas by expansion, with no heat exchange between the parcel and surrounding air.

ADIABATIC HEATING
Warming of a parcel of gas by compression, with no heat exchange between the parcel and surrounding air.

ADIABATIC PROCESS
A process where a parcel of air changes temperature due to a change in pressure and volume (expansion and compression), with no heat exchange between the parcel and surrounding air.

ADVECTION
The horizontal transport of any property in the atmosphere by the movement of air.

ADVECTION FOG
Fog resulting from the movement of moist air over a cold surface and the consequent cooling of the air to dew-point. Also refers to fog being transported by local winds from one locality to another.

AIR DENSITY
The mass of air per unit volume.

AIR MASS
An extensive body of air with horizontally uniform temperature and moisture characteristics; in addition the vertical temperature and moisture variations are approximately the same over its horizontal extent.

ALTIMETER
An instrument used to determine altitude from atmospheric pressure.

ALTITUDE
The vertical distance from mean sea level to an object aloft.

ALTOCUMULUS
Middle level layered cloud with rippled elements, generally white with some shading.

ALTOCUMULUS CASTELLANUS
level cloud with vertical turret type development that forms from altocumulus clouds.

ALTOSTRATUS
Middle level cloud appears as a grey sheet.

ANABATIC WIND
An uphill wind generated by the heating of a sloping surface.

ANEMOMETER
An instrument used to measure the speed of the wind.

ANEROID BAROMETER
An instrument used to measure atmospheric pressure.

ANOMALOUS PROPAGATION
The non-standard propagation of a beam of energy, radio or radar, under certain atmospheric conditions, appearing as false (non-precipitation) echoes.

ANTI-ICING EQUIPMENT
Aircraft equipment, such as heating elements and flexible rubber strips, used to prevent or clear structural icing.

ANTICYCLONE (HIGH)
A closed area of high pressure. The wind rotates about the centre anticlockwise in the southern hemisphere and clockwise in the northern hemisphere.

ANVIL
The upper portion of a cumulonimbus cloud that becomes flat and spreads-out under the tropopause: sometimes for hundreds of kilometers downstream from the parent cloud. It appears smooth or fibrous and often resembles a blacksmith's anvil. It indicates the mature or decaying stage of a thunderstorm.

AIRCRAFT ICING
Any deposit of ice forming on an aircraft.

ATMOSPHERE
The gaseous portion of the physical environment that encircles the earth. The divisions of the atmosphere include the troposphere, the stratosphere, the mesosphere, the ionosphere, and the exosphere.

ATMOSPHERIC PRESSURE
The total weight of the atmosphere above the point of measurement.

BACKING
A counterclockwise shift in the wind direction.

BAROMETER
An instrument for measuring atmospheric pressure. Two examples are the aneroid barometer and the mercurial barometer.

BLOWING DUST
Dust that is raised locally by the wind.

BLOWING SNOW
Snow that is raised locally by the wind to more than 2 metres.

BOILING POINT
The temperature at which a liquid changes to the vaporous state. The boiling point of pure water at standard pressure is 100°C

BOUNDARY LAYER
The lowest layer of the earth's atmosphere, usually below 3,000 feet where frictional influences between the earth and atmosphere are large.

BUOYANCY
The property of an air parcel that allows it to rises freely from one level to another in the atmosphere.

BROKEN CLOUD
The amount of sky cover for a cloud layer, between five and seven okta.

BUYS BALLOT'S LAW
Describes the relationship of the wind direction to the pressure distribution. In the southern hemisphere, if an observer stands with his/her back to the wind, lower pressure is to the right.

CALM
Still air.

CARBURETTOR ICING
Occurs when moist air is drawn into the carburetor and is cooled below 0°C and the moisture freezes.

CEILOMETER
A cloud height measuring system.

CELSIUS TEMPERATURE SCALE
A temperature scale where water at standard pressure of 1013.25 hPa, has a freezing point of 0° and a boiling point of +100°. Abbreviated as °C.

CHANGE OF STATE
The change in the form of water, i.e. water to vapour, ice to water, ice to vapour and vice versa.

CIRROCUMULUS
High-level cloud composed of ice crystals; appearing from the ground as very small elements in the form of grains or small ripples.

CIRROSTRATUS
High-level cloud composed of ice crystals, appearing from the ground as a transparent sheet or veil and creating the halo phenomena around the sun or moon.

CIRRUS
High-level cloud, composed of ice crystals; appearing from the ground as white tufts or filaments.

CLEAR AIR TURBULENCE
Non-convective, wind shear turbulence, encountered in air where no clouds are present; abbreviated as CAT.

CLEAR ICE
A glossy, clear, or translucent ice formed by the relatively slow freezing of large supercooled water droplets. The droplets spread out over an object, such as an aircraft wing's leading edge, prior to complete freezing and forms a sheet of clear ice.

COLD AIR ADVECTION
The horizontal movement of colder air into a location of warmer air.

COLD FRONT
The leading edge of an advancing cold air mass that is replacing warmer air.

CONDENSATION
Change of state from vapour to liquid.

CONDENSATION NUCLEI
Tiny particles upon which vapour condenses.

CONDENSATION LEVEL
The level that an adiabatically lifted air parcel will become saturated.

CONDITIONAL INSTABILITY
Stable unsaturated air that will become unstable if saturated.

CONDUCTION
The transfer of heat through a substance or between one substance and another, by being in contact with another.

CONSTANT PRESSURE CHART
A weather chart representing conditions on a constant pressure surface.

CONTACT COOLING
The process where heat is conducted away from warmer air to a colder surface.

CONTINENT
A large land mass.

CONTINENTAL AIR MASS
An air mass with continental characteristics.

CONTOUR
A line joining points of equal value on a surface.

CONTRAIL
Acronym for CONdensation TRAIL.

CONVECTIVE CLOUD
A cloud with vertical development that forms in an unstable environment.

CONVECTIVE CONDENSATION LEVEL
The lowest level at which condensation will occur as a result of convection due to surface heating; abbreviated as CCL.

CONVERGENCE
The condition that exists as a result of the net horizontal inflow of air into a region. Convergent winds at lower levels are associated with upward motion.

COORDINATED UNIVERSAL TIME
The standard world time beginning at Greenwich, England, home of the Royal Observatory. Abbreviated as UTC.

CORIOLIS FORCE (EFFECT)
An apparent force on a moving particle that arises solely from the earth's rotation acting as a deflecting force. It acts to the left in the southern hemisphere and to the right in the northern hemisphere. It is greatest at the poles and nonexistent at the equator.

CUMULONIMBUS
A vertically developed cumulus cloud, often capped by an anvil-shaped cirriform cloud. Also called a thunderstorm cloud, it is frequently accompanied by heavy showers, lightning, thunder, and sometimes hail, tornadoes or strong, gusty winds; abbreviated as CB

CUMULUS
Clouds characterised by their flat bases and dome or cauliflower shaped upper surfaces. Small, separate cumulus are associated with fair weather; abbreviated as CU.

DENSITY
The weight of air per unit volume.

DEPOSITION
The state where water vapour changes directly to ice.

DENSITY ALTITUDE
The altitude at which a given density is found in the standard atmosphere.

DEW
Water condensation in the form of small water drops that form on grass and other objects near the ground when the temperature has fallen to the dew point.

DEW POINT
The temperature to which air must be cooled to become saturated.

DIURNAL
Pertaining to differences that occur from day to night during a twenty-four hour cycle

DIVERGENCE
Horizontal outflow of air from a particular region. Divergence at lower levels is associated with a downward movement of air.

DOLDRUMS
A nautical term for the equatorial trough. This area typically has calm or light and variable winds.

DOWNBURST
A severe localised downdraft of wind from a thunderstorm or shower with a diameter of greater then 4 kilometres. This outward burst of cool air creates damaging winds at or near the surface.

DOWNDRAFT
A descent of cool air associated with cumulus cloud.

DOWNSLOPE WIND
Gusty winds directed down a slope, often used to describe winds produced by processes larger than the scale of the slope.

DRIFTING SNOW
Snow particles blown from the ground by the wind to a height of less than two metres.

DRIZZLE
Slowly falling precipitation in the form of tiny water droplets with diameters less than 0.5 millimeters. It usually falls from stratus or stratocumulus clouds and is often associated with low visibility and fog. In aviation observations and forecasts it is reported as DZ.

DRY ADIABAT
The line on a chart that depicts the lifting of dry air. As a parcel rises adiabatically, its pressure decreases and its temperature falls due to the expansion of the air parcel. When an air parcel is unsaturated and rises, the temperature decreases at a rate of about 3°C per 1000 feet).

DRY LINE
The boundary between dry and moist air masses.

DUST
Small particles of earth or other matter suspended in the air. In aviation observations and forecasts it is reported as DU.

DUST DEVIL
A small, rapidly rotating column of wind, made visible by the dust, dirt or debris picked up. It usually occurs in arid or semi-arid areas and is most likely to develop on clear, dry, hot afternoons in response to surface heating it is reported as PO.

DUSTSTORM
A condition characterized by strong winds and dust-filled air over a large area. Visibility is reduced to below 5000 metres. In aviation observations and forecasts it is reported as DS.

ECHO
In radar, a general term for the appearance, on a radar display, of the radio signal reflected from a target.

EDDY
A small disturbance in the wind that can produce turbulent conditions.

ELEVATION
The distance between mean sea level and a point on the earth's surface.

EQUATOR
The geographic circle at 0 degrees latitude on the earth's surface.

EQUILIBRIUM LEVEL
The level at which a parcel of air is no longer buoyant and ceases to rise in the atmosphere.

EQUATORIAL TROUGH
The quasi-continuous area of low pressure between the subtropical high pressure belts of the northern and southern hemispheres.

EVAPORATION
The physical process by which a liquid, such as water is transformed into the gaseous state.

EYE
An area of clear skies that develops in the centre of a tropical cyclone, charaterised by light winds and no rainfall.

EYE WALL
An organized band of that surrounds the eye, or centre, of a tropical cyclone.

FAHRENHEIT TEMPERATURE SCALE
The temperature scale where water at the standard sea level pressure of 1013.25 hPa has a freezing point of +32° and a boiling point of +212°. (Abbreviated °F).

FEEDER BANDS
The lines or bands of thunderstorms that spiral into and around the centre of a tropical cyclone.

FEW
The term used to indicate cloud of between one octa and two octa, based on the summation layer amount for that layer.

FOEHN
A warm, dry downslope wind descending the lee side of a mountain range.

FOG
A visible aggregate of small water droplets suspended in the atmosphere at or near the surface of the earth, reducing horizontal visibility to less than 1000 metres. In aviation observations and forecasts it is reported as FG.

FREEZING DRIZZLE
Drizzle, falling as a liquid, but freezing on impact with the colder ground or other exposed surfaces to form a coating of glaze. In aviation observations and forecasts it is reported as FZDZ.

FREEZING POINT
The temperature at which a liquid solidifies under any given set of conditions. Pure water under the standard pressure of 1013.25 hPa, freezes at 0°C or 32°F.

FREEZING PRECIPITATION
Any form of liquid precipitation that freezes upon impact with a solid surface, such as the ground or other exposed surfaces.

FREEZING RAIN
Rain that falls as liquid and freezes upon impact to form a coating of glaze on the colder ground or other exposed surfaces. In aviation observations and some forecasts it is reported as FZRA.

FRICTION
The drag or resistance of the earth on the atmosphere.

FRICTION LAYER (or boundary layer)
The thin layer of atmosphere adjacent to the earth's surface affected by friction. Surface friction is effective in slowing down wind up to about 3,000 feet above the ground.

FRONT
The transition zone or interface between two air masses of different densities.

FRONTAL PASSAGE
The passage of a front over a specific point on the surface. A change in dew point and temperature, a shift in wind direction, and a change in atmospheric pressure reflect it.

FUNNEL CLOUD
A violent, rotating column of air visibly extending toward the ground (but not in contact with it) from the base of a towering cumulus or cumulonimbus. In aviation observations and some forecasts it is reported as FC.

GEOSTATIONARY SATELLITE
A weather satellite in a west to east orbit at an altitude of 35786 km that maintains the same position over the equator.

GEOSTROPHIC WIND
The horizontal wind at which the Coriolis force exactly balances the horizontal pressure force.

GRADIENT WIND
Any steady horizontal air motion along curved parallel isobars or contours in an unchanging pressure or contour field, assuming there is no friction and no divergence or convergence.

GREENWICH MEAN TIME
Abbreviated as GMT, but now replaced by Coordinated Universal Time (UTC).

GROUND CLUTTER
A pattern of radar echoes from fixed ground objects such as buildings, hills or other objects on or close to the ground.

GUST
A sudden increase of wind speed, of at least 10 knots, lasting for only a few seconds.

GUST FRONT
The leading edge of a small scale pressure dome separating the outflow of cool, gusty surface winds (produced by thunderstorm downdrafts) from the environmental winds.

HAIL
Precipitation that originates in convective clouds, such as cumulonimbus, in the form of balls or irregular pieces of ice. In aviation observations and forecasts it is reported as GR.

HAZE
Dust and/or smoke particles suspended in the air. In aviation observation and in forecasts it is reported as HZ.

HIGH PRESSURE SYSTEM
An area of pressure maximum with diverging and anti-clockwise winds in the southern hemisphere and clockwise in the northern hemisphere.

HOARFROST
A deposit of interlocking ice crystals formed by direct deposition on objects.

ICING
The forming or depositing of ice on an object or within aircraft carburetors.

INFRARED
Long wave, electromagnetic radiation emitted by all objects. May be referred to as IR.

INSOLATION
Solar radiation or heating received at the earth's surface. The name is derived from INcoming SOLar radiATION.

INSTABILITY
The state of the atmosphere, when air parcels displaced vertically, will freely accelerate upward, often forming cumulus clouds and possibly thunderstorms.

INSTRUMENT FLIGHT RULES
A set of regulations governing the procedures and operational control of aircraft, conducting a flight by instruments rather than by sight. Abbreviated as IFR

INTERNATIONAL STANDARD ATMOSPHERE
A hypothetical vertical distribution of atmospheric temperature, pressure and density that by international agreement is taken to be representative of the atmosphere for purposes of pressure altimeter calibrations, aircraft performance calculations, ballistic tables etc. Abbreviated as ISA.

INTERTROPICAL CONVERGENCE ZONE
A region where southeast and northeast trade winds meet. Usually located between 10 degrees north and south of the equator. It is a broad area of low pressure. It fluctuates in location, so that during the southern hemisphere summer, the ITCZ moves southward over northern Australia. Abbreviated as ITCZ.

INVERSION
An increase in temperature with increasing altitude, which is opposite to the usual decrease of temperature with increasing altitude.

ISOBAR
A line on a chart connecting points of equal pressure.

ISOTACH
A line on a chart connecting points of equal wind speed

ISOTHERM
A line on a chart connecting points of equal temperature.

JET STREAM
An area of strong winds, concentrated in a relatively narrow band, most commonly observed in the upper troposphere and near breaks in the tropopause.

KATABATIC WIND
A drainage wind generated by air being cooled by conduction along a slope. The cooled air flows downhill as a katabatic wind.

KELVIN-HELMHOLTZ WAVE
A waveform disturbance that arises from Kelvin-Helmholtz instability.

KELVIN-HELMHOLTZ INSTABILITY
An instability of the basic flow of a fluid in two parallel streams of different speed and densities.

KELVIN-HELMHOLTZ BILLOWS
Cloud forms that arise from Kelvin-Helmholtz waves.

KELVIN TEMPERATURE SCALE
A temperature scale, with a freezing point of +273° and a boiling point of +373°. It is used primarily for scientific purposes. Abbreviated as °K.

KNOT
A unit of speed equivalent to 1.852 kilometers per hour.

LAND BREEZE
A diurnal coastal or lake breeze that blows offshore. It is caused by the temperature differences between water surfaces and adjacent land.

LAPSE RATE
The rate of change of temperature with height in the atmosphere.

LATENT HEAT
The energy released or absorbed during a change of state.

LATITUDE
The angular distance, subtended at the earthÅfs center, along the meridian from a point on the earth to the equator. The equator is designated as zero degrees and the poles as 90 degrees

LEE/LEESIDE/LEEWARD
The side of an obstacle that is furthest away from the wind.

LENTICULAR CLOUD
A cloud resembling a smooth lense with sharp outlines and more or less isolated. Lenticular clouds are mostly caused by mountain waves. They are indicative of turbulence down-stream of a barrier.

LEVEL OF FREE CONVECTION
The level at which a parcel of saturated air becomes warmer than the surrounding air and begins to rise freely. Abbreviated as LFC.

LIFTING CONDENSATION LEVEL
The height at which a parcel of moist air becomes saturated. Abbreviated as LCL.

LIGHTNING
A transient, high-current electric discharge with path lengths measured in kilometres. Lightning can occur between cloud and ground, between clouds, within a single cloud, or between a cloud and surrounding air.

LONGITUDE
The location east or west in reference to the Prime Meridian, which is designated as zero degrees longitude. Time zones are correlated to longitude.

LOW LATITUDES
The latitude belt between the equator and 30 degrees north and south of the equator.

LOW LEVEL JET
A strong wind concentrated in relatively narrow bands near the surface. Abbreviated as LLJ.

LOW PRESSURE SYSTEM
An enclosed area of low pressure that has converging winds rotating clockwise in the southern hemisphere and anticlockwise in the northern hemisphere.

MARITIME AIR MASS
An air mass sourced from the sea that has developed over and originated over an extensive water surface.

MECHANICAL TURBULENCE
Disrupted air-flow caused by frictional interference.

MERIDIONAL FLOW
Atmospheric circulation in which the north and south component of motion is pronounced.

METAR
The primary observation code used in aviation for reporting surface meteorological data. Also known as Aviation Routine Weather Reports. Abbreviation for METeorological Aerodrome Report.

MICROBURST
A severe downburst of wind, usually from a thunderstorm. It covers an area less than 4 kilometers in diameter and is of short duration, usually less than 5 minutes.

MIST
A collection of small water droplets suspended in the atmosphere.

MIXING RATIO
An absolute measure of the amount of water vapor in an air parcel for a given temperature and pressure.

MOIST ADIABAT
The line on a chart that depicts the change in temperature of saturated air as it rises and undergoes cooling due to adiabatic expansion. As saturated air rises, the temperature changes at a rate about 2°C per 1,000 feet.

MONSOON
The seasonal shift of winds created by the great annual temperature variation that occurs over large land areas compared with associated ocean surfaces. The monsoon is strongest on the southern and eastern sides of Asia.

MOUNTAIN WAVE
An atmospheric gravity wave that forms in the lee of mountains. Sometimes it is marked by lenticular clouds above and to the lee side of mountain barriers.

MULTICELL STORM
A storm system composed of two or more convective cells at various stages of their life cycle.

NIMBOSTRATUS
Low or middle level thick cloud with heavy precipitation or snow.

OCCLUDED FRONT
A front formed when one front overtakes another.

OROGRAPHIC LIFTING
Where the flow of air is forced up and over barriers such as highlands or mountains.

PARCEL
A small self-contained volume of air responding to meteorological processes as a single entity.

PILOT REPORT
A report of in-flight weather by an aircraft pilot or crew member. Referred to as an AIREP.

POLAR AIR MASS
An air mass that forms over a high latitude region. Continental polar air (Pc) is formed over cold surface regions and is typically very stable with low moisture.

POLAR FRONT
A semi-continuous, semi-permanent boundary between polar and subtropical air masses.

POLAR-FRONT JET
A jet stream associated with cold fronts and occurs mainly in winter. Its core tends to be at an altitude of 30 000 feet over Australia; abbreviated as PFJ

POLAR-ORBITING SATELLITE
A satellite whose orbit passes over both of the earth's poles.

PRECIPITATION
Any and all forms of water, liquid or solid, that falls from clouds and reaches the ground.

PRE-FRONTAL SQUALL LINE
A line of thunderstorms that precedes an advancing cold front, in the warm sector, having an orientation more or less parallel to the cold front.

PRE-FRONTAL TROUGH
An elongated area of relatively low pressure preceding a cold front that is usually associated with a shift in wind direction.

PRESSURE ALTIMETER
An aneroid barometer calibrated to indicate altitude in feet instead of units of pressure. It is read accurately only in a standard atmosphere and when the correct altimeter setting is used.

PRESSURE ALTITUDE
The altitude in the ISA at which a given pressure will be observed. It is the indicated altitude of a pressure altimeter.

PRESSURE GRADIENT
The pressure change that occurs over a fixed distance.

PREVAILING WIND
A wind that blows from one direction more frequently than any other during a given period.

PROGNOSTIC CHART
A forecast weather chart. Commonly known as a prog chart.

QUASI-STATIONARY FRONT
A front which is nearly stationary or moves very slowly.

RADAR
Acronym for RAdio Detection And Ranging. An electronic instrument used to detect distant objects and measure their range by detecting scattered or reflected radio energy.

RADIATION
The process by which energy is propagated through any medium by virtue of the wave motion in that medium. Electromagnetic radiation, which emits heat and light, is one form.

RADIATIONAL COOLING
The cooling of the earth's surface and the adjacent air. It happens when the earth's surface suffers a net loss of heat due to outgoing radiation.

RADIATION FOG
Fog that is created when radiational cooling at the earth's surface lowers the temperature of the air near the ground to or below its dew-point.

RAIN
Precipitation in the form of liquid water droplets greater than 0.5 mm diameter. If widely scattered, the drop size may be smaller. It is reported as RA in an observation and forecast.

RELATIVE HUMIDITY
The ratio of the existing amount of water to that which could be held by a parcel of air. It is usually expressed as a percentage.

RESOLUTION
In relation to radar, it is the ability to read two distinct targets separately. The clearer the resolution, the nearer the two objects can be to each other and still be distinguishable.

RIDGE
An elongated area of high pressure.

RIME
Ice formed by the rapid freezing of supercooled water droplets when they contact an exposed object, forming a white opaque granular deposit of ice.

ROLL CLOUD
Low-level, horizontal, tube-shaped cloud. Usually associated with a thunderstorm gust front, they are completely detached from the base of the cumulonimbus cloud.

ROTOR CLOUD
A cloud formation found in the lee of a mountain or similar barrier. The air rotates around a horizontal axis, creating turbulence.

RUNWAY VISUAL RANGE
The maximum distance at which the runway, or the specified lights or markers delineating it, can be seen from a position above a specified point on its centerline. Abbreviated as RVR.

ST. ELMO'S FIRE
A luminous and often audible electric discharge that is sporadic in nature. It occurs from objects, especially pointed ones, when the local electrical field is high. It often occurs during stormy weather and might be seen on the extremities of aircraft, lightning rods, and steeples.

SANDSTORM
Low-level blowing sand: that reduces visibility. In aviation observations and some forecasts it is reported as SS.

SATURATE
To charge something to the point where no more can be absorbed, dissolved, or retained. In meteorology, it is used when discussing the amount of water vapor in a volume of air.

SATURATED ADIABATIC LAPSE RATE (SALR)
The rate of decrease of temperature for saturated air being lifted adiabatically

SCATTERED
The amount of sky cover for a cloud layer between three and four okta, based on the summation layer amount for that layer.

SEA-BREEZE
A diurnal coastal breeze that blows onshore.

SEA-BREEZE FRONT
The discontinuity in temperature and humidity that marks the leading edge of the intrusion of cooler, more moist marine air associated with a sea-breeze.

SEA FOG
Advection fog that forms in warm moist air, cooled to saturation by the underlying colder water surface.

SEA LEVEL
The height or level of the sea surface after averaging out the short-term variations due to wind waves. It is used as a reference for elevations above and below.

SEA LEVEL PRESSURE
The atmospheric pressure at mean sea level.

SEVERE THUNDERSTORM
A thunderstorm with winds measuring 48 knots (90 km/h) or greater, 2 cm hail or larger, or tornadoes. Severe thunderstorms may also produce torrential rain and frequent lightning.

SHEAR
Wind shear refers to the change in wind speed or direction within a short distance. It can occur vertically or horizontally.

SHOWER
Precipitation from a convective cloud that is characterised by its sudden beginning and ending, changes in intensity, and rapid changes in the appearance of the sky. It occurs in the form of rain (SHRA), snow (SHSN), or hail (SHGR). In aviation observations and some forecasts it is reported as SH.

SKEW T-LOG P DIAGRAM
A thermodynamic diagram with a skewed temperature scale and the logarithm of pressure as coordinates. It is used to evaluate and forecast air parcel behaviour. Some values that can be determined are the Convective Condensation Level (CCL), the Lifting Condensation Level (LCL), and the Level of Free Convection (LFC).

SMOKE
Small particles produced by combustion that are suspended in the air. A transition to haze may occur when the smoke particles have traveled great distance and when the larger particles have settled out. The remaining particles become widely scattered through the atmosphere. In aviation observations and some forecasts it is reported as FU.

SNOW
Frozen precipitation in the form of white or translucent ice crystals in complex branched hexagonal form. It most often falls from stratiform clouds, but can fall as snow showers from cumuliform ones. It usually appears clustered into snowflakes. In aviation observations and some forecasts it is reported as SN.

SQUALL
A sudden onset of strong winds with speeds increasing to at least 16 knots and sustained at 22 or more knots for at least one minute. The intensity and duration is longer than that of a gust. In aviation observations and some forecasts it is reported as SQ.

SQUALL LINE
A narrow band or line of active thunderstorms, either continuous or with breaks, that is not associated with a cold front.

St. ELMOS FIRE
A corona or point discharge, that occurs when the environmental electric field is high.

STABLE ATMOSPHERE
A state of the atmosphere occuring when a rising air parcel becomes denser than the surrounding air. It will then return to its original position.

STANDING WAVE
An atmospheric wave that is stationary with respect to the atmosphere.

STEAM FOG
A type of advection fog that is produced by evaporation when cool air passes over a warm wet surface and the fog rises, giving the appearance of steam.

STRATIFORM
Clouds that exhibit extensive horizontal development, in contrast to the vertically developed cumuliform type.

STRATOCUMULUS
A low cloud composed of layers or patches of cloud elements. It can form from cumulus clouds becoming more stratified and often appears as regularly arranged rounded, or roll-shaped elements with relatively flat tops and bases. It is light or dark gray in color, depending on the size of the water droplets and the amount of sunlight that is passing through it. Abbreviated as SC.

STRATOPAUSE
The boundary zone between the stratosphere and the mesosphere. Characterised by a decrease in temperature with increasing altitude.

STRATOSPHERE
The layer of the atmosphere located between the troposphere and the mesosphere, characterized by a slight temperature increase and absence of clouds.

STRATUS
A sheet like cloud that does not exhibit individual elements. Abbreviated as ST.

SUBLIMATION
The process of ice changing directly into water vapour.

SUBSIDENCE
A sinking or descending motion of air

SUBTROPICAL JET
A band of relatively strong winds concentrated above an altitude of 30 000 feet over the subtropical high pressure belt.

SUPERCELL
A severe thunderstorm characterised by a rotating, long-lived, intense updraft. They are capable of producing extremely large hail, damaging straight-line winds, and violent tornadoes.

SUPERCOOLING
The reduction of the temperature of any liquid below the freezing point.

SURFACE BOUNDARY LAYER
The lowest layer of the earth's atmosphere, usually up to 3,000 feet where the wind is influenced by the friction of the earth's surface and the objects on it.

SYNOPTIC CHART
Any map or chart that depicts meteorological or atmospheric conditions over a large area at a given time.

THERMOSPHERE
A thermal classification, it is the layer of the atmosphere located between the mesosphere and outer space. It is a region of steadily increasing temperature with height, and includes all of the exosphere and most, if not all, of the ionosphere.

THUNDER
The sound emitted by rapidly expanding gases along the channel of a lightning discharge.

THUNDERSTORM
Produced by a cumulonimbus cloud, characterized by thunder, lightning, gusty surface winds, turbulence, hail, icing, precipitation, moderate to extreme up and downdrafts, and under the most severe conditions, microbursts and/or tornadoes.

TORNADO
A rotating column of air in contact with and extending between a convective cloud and the ground. It is the most destructive of all storm-scale atmospheric phenomena although microbursts can be just as severe over a shorter life time.

TRADE WINDS
Two belts of prevailing wind that blow from the subtropical high pressure centres towards the equatorial trough. Primarily lower-level winds, they are characterised by their great consistency of direction. In the northern hemisphere, the trades blow from the northeast, and in the southern hemisphere, from the southeast.

TROPICS
The region of the earth located between the Tropic of Cancer, at 23.5 degrees north and the Tropic of Capricorn, at 23.5 degrees south.

TROPICAL AIR MASS
An air mass that forms in the tropics or subtropics over the low latitudes. Maritime tropical air is produced over oceans and is warm and humid, while continental tropical air is formed over arid regions and is very hot and dry.

TROPICAL CYCLONE
Tropical cyclones are non-frontal low pressure systems that develop over tropical waters with winds of 34 knots or more. In Australia the term severe tropical cyclone is used when winds reach or exceed 64 knots.

TROPICAL DISTURBANCE
An area of organized convection, originating in the tropics or occasionally the subtropics, that maintains its identity for 24 hours or more, but has no closed wind circulation. It is often the first developmental stage of a tropical storm, or cyclone.

TROPIC OF CANCER
Located at 23.5 degrees north. The most northern point on the earth where the sun is directly overhead on the 21 June.

TROPIC OF CAPRICORN
Located at 23.5 degrees south. The most southern point on the earth where the sun is directly overhead on the 22 December,

TROPOPAUSE
The boundary zone or transition layer between the troposphere and the stratosphere.

TROPOSPHERE
The lowest layer of the atmosphere located between the earth's surface to approximately 35000 feet into the atmosphere. Characterised by clouds and weather, temperature generally decreases with increasing altitude.

TROUGH
An elongated area of low atmospheric pressure.

TURBULENCE
The irregular and instantaneous motions of air made up of small eddies that travel in the general air-flow. Atmospheric turbulence is caused by apparent random fluctuations in the wind flow.

UNSTABLE ATMOSPHERE
An atmosphere in which air parcels rise buoyantly. Occurs when a rising air parcel becomes less dense than the surrounding air.

UPDRAFT
A small-scale current of air with marked vertical motion.

VALLEY BREEZE
An anabatic wind, it is formed during the day by the heating of the valley floor. As the ground becomes warmer than the surrounding atmosphere, the lower levels of air heat and rise, flowing up the mountainsides.

VAPOUR PRESSURE
The pressure exerted by gaseous molecules. In meteorology, it is that part of total atmospheric pressure due to water vapour content.

VEERING
A clockwise shift in the wind direction.

VIRGA
Streaks or wisps of precipitation, such as water or ice particles, that fall from clouds but evaporate before reaching the ground.

VISIBILITY
A measure of the opacity of the atmosphere, and therefore, the greatest distance one can see objects with the unaided eyesight.

VISUAL FLIGHT RULES
Rules that govern an aircraft flight under conditions that allow navigation by visual reference to the earth's surface at a safe altitude and with sufficient horizontal visibility; abbreviated as VFR.

WAKE TURBULENCE
A disruption of airflow behind a moving aircraft, causing turbulence.

WALKER CIRCULATION
An east-west circulation induced by the contrasts between the warm waters of the western Pacific and the cooler waters of the eastern Pacific.

WARM ADVECTION
The horizontal movement of warmer air into a location.

WARM FRONT
The leading edge of an advancing warm air mass that is replacing a relatively colder air mass.

WATER VAPOUR
Water in gaseous form. It is one of the most import constituents of the atmosphere.

WAVELENGTH
The distance between two successive wave crests separated by a trough.

WEATHER FORECAST
A prediction of the future state of the atmosphere.

WHIRLY WIND
A small-scale, rapidly rotating column of wind, formed thermally and most likely to develop on clear, dry, hot afternoons. Often called a dust devil when made visible by the dust, dirt or debris it picks up.

WHITEOUT
Occurs when visibility is near zero. Clouds and the surface seem to blend; the horizon is erased and a completely white vista is created.

WIND DIRECTION
The direction from which the wind is blowing.

WIND SHEAR
A wind direction and/or speed change over a vertical or horizontal distance.

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