4 Cloud forms

Clouds make visible the motions of the atmosphere. Cloud forms, structure and development give the informed observer an indication of the present or future weather conditions. To the pilot, clouds may show areas of turbulence and levels of wind shear—both potential hazards. For the interested layperson, a knowledge of the processes involved in the formation of clouds can heighten appreciation of the many beautiful cloudscapes observed.

Form and classification of clouds

Despite the great variety of cloud forms observed from day to day or even hour to hour, these forms generally fall into one or other of three basic groups—the 'streak', the 'sheet' and the 'heap'. The streak is characteristic of ice clouds, the sheet is produced by a slow widespread lifting of air, and the heap is produced by local convective up-currents. Once formed, the cloud may be altered by internal movements which will be described later.

The internationally agreed nomenclature is based on three basic cloud forms, and follows one proposed in 1803 by Luke Howard, a London pharmacist. He proposed the names *stratus* (Latin—layer), *cumulus* (Latin—pile), and *cirrus* (Latin—hair). He also used the term *nimbus*, for rain cloud, but this is now used only in combination i.e. *nimbostratus*—a rainy layer cloud; *cumulonimbus*—a rainy heap cloud. Various other combinations are also used, with the term cumulus being extended to cover lump, rolled, or billowy clouds. In addition the prefix 'alto' has been introduced to designated clouds in the middle troposphere. There are now ten main cloud types recognised:

cirrus	**Ci**	—	hair-like or streak cloud
cirrostratus	**Cs**	—	layer of streak clouds
cirrocumulus	**Cc**	—	lumpy or billowy streak clouds
altostratus	**As**	—	layer at medium levels
altocumulus	**Ac**	—	billowy cloud at medium levels
stratus	**St**	—	layer cloud
cumulus	**Cu**	—	heap cloud
stratocumulus	**Sc**	—	billowy or rolled layer
nimbostratus	**Ns**	—	rainy layer cloud
cumulonimbus	**Cb**	—	rainy heap cloud

The terms cirriform, stratiform and cumuliform are convenient collective names for those cloud types whose main characteristics are those of streak, layer and heap clouds respectively. For example, *cirrostratus, altostratus, nimbostratus* and *stratus* are all stratiform clouds.

Precipitation falls from stratiform clouds as drizzle, rain or snow. It generally has a uniformity, similar to that of the appearance of the clouds, being intermittent or continuous, with no abrupt change in intensity. Cumuliform clouds, on the other hand, give showers, sometimes heavy with thunder and hail, and abrupt changes of

rainfall intensity are normal. Therefore, forecasting precipitation from this latter type of cloud is often difficult.

Conditions in the troposphere sometimes favour only stratiform clouds, or at other times only cumuliform clouds. However, there are many times when stratiform and cumuliform clouds mingle. For instance, cumuliform clouds often extend vertically through one or more layers of stratiform clouds; also high altitude cirrostratus or altostratus cloud sheets sometimes form an extensive canopy above cumulus in the lower troposphere.

Formation of cloud

All cloud is formed as a result of cooling of the air to its condensation point. This cooling may occur in a number of ways but most frequently by expansion.

Pressure is a measure of the weight of atmospheric air above a point, so that with increasing altitude the pressure decreases. In the lower troposphere the rate at which it decreases is about 1 hPa (or mb) for every 10 metres. Thus air which is rising is subject to reducing pressure and expands as a result. Expansion is a cooling process, so that the temperature of rising air decreases. The rate at which it decreases is independent of the temperature of the surrounding air, and is constant for unsaturated air, so that unsaturated air always cools at 10°C per kilometre as it rises. This is known as the dry adiabatic lapse rate.

As it cools the air becomes moister, and eventually saturation is reached. Any further cooling produces condensation, and visible cloud forms. Condensation also releases latent heat, which partly serves to warm the rising air. Below about three kilometres this warming is sufficient to reduce the rate of cooling to about half the dry adiabatic lapse rate i.e. 5°C/km. At higher levels with colder temperatures, less moisture is available in the air for condensation, so that the amount of warming is reduced, and in the high troposphere the rate of cooling is very close to the dry adiabatic lapse rate. The rate at which saturated air cools as it rises is known as the saturated adiabatic lapse rate.

The temperature difference between the rising air and the surrounding air determines to a large degree the shape and appearance of a cloud. If the rising air is warmer than the surrounding air, then it is more buoyant and will continue to rise, pushing up vigorous towers. If on the other hand the temperature of the surrounding air is higher than that of the rising air, the rising air will have no buoyancy, and hence will resist the upward movement and sink as soon as it is able. It is this condition which gives the characteristic lens shaped clouds over hills.

When air is rising slowly over a large area, the whole air mass is cooled simultaneously at the same rate, so that one part does not usually have buoyancy relative to another and a layer cloud results. In such a layer the lapse rate is likely to be the saturated adiabatic.

The great majority of clouds are formed in rising air: lifting of the air may be due to one, or sometimes more, of several processes—convection, orographic lifting, large scale ascent, and turbulence. Processes which produce cloud without lifting are advection, expansion, and mixing of air at different temperatures.

Ice crystal clouds

Although temperatures near the ground may be quite high, decrease of temperature with height means that above a certain level temperatures are constantly below freezing. In New Zealand the level above which the temperature is normally below freezing is about 2-3 km in winter and 3-4 km in summer. Many clouds occur in these sub-freezing regions and we might therefore expect them to be composed of ice crystals—but this is not necessarily the case. Condensing vapour rarely, if ever, produces ice crystals directly: above a temperature of about -40°C water droplets are always formed, of which only a few subsequently freeze to ice crystals, but below -40°C almost all the droplets turn immediately to ice crystals.

In a cloud composed of a combination of water droplets and ice crystals, it can be shown that the ice crystals will grow at the expense of the droplets and soon become much larger—possibly attaining the size of snow crystals in an hour. These large crystals begin to fall, so that a cloud composed predominantly of supercooled drops will soon release trails of snow crystals and eventually become transformed into a pure ice cloud.

The readiness of water vapour to condense on to ice crystals is seen in the ability of crystals to grow in air which is not moist enough to produce droplet cloud, but is moist enough to support the growth of crystals which fall from a cloud above. It is therefore common to see dense trails of ice crystals below a small cloudlet. Plate 10 shows cirrus clouds with trails of ice crystals. The direction of the falling snow crystals often shows the variation of wind with height, with the parent cloud often moving ahead of the trail.

Another characteristic of ice crystals is seen in the silky appearance of ice clouds. At the edges of water droplet clouds rapid evaporation into the surrounding drier air leads to crisp well-defined edges. Between ice clouds however, the air is often moist enough to at least sustain the ice crystals and sometimes to allow further growth. Thus ice crystal clouds have diffuse edges, and usually persist for long periods. Because of this, the growth of cirrus clouds over a large part of the sky from aircraft condensation trails may sometimes be observed, while streamers of ice cloud may extend hundreds of miles downstream from their formation point, often in association with jet streams.

Formation processes

Convection

Convection occurs when the atmosphere is heated by contact with a warmer surface e.g. when the ground is heated by sunshine, or when cool air moves over a warm sea. The warmed air near the ground becomes buoyant, and rises as bubbles or masses of air which penetrate and mix with the cooler air above. Such rising masses are called 'thermals'. A thermal has the form of a ring-shaped mass of air continually turning itself inside out, with the inside continuously coming to the upper surface and there being mixed with the air in its path. With mixing and dragging of air into the base (known as entrainment) the thermal grows bigger as it rises, Fig. 18a.

When a thermal reaches the condensation level it becomes visible as a cumulus cloud. Note that the condensation level is horizontal, so that although there are turbulent stirrings below the cloud, the base of it is quite flat. Figure 18b shows that a bulging cauliflower-like top is produced by mixing on the upper surface. Features on this top can be seen to form, move towards the edges and disappear. Because the outside of the cloud is mixing with drier air, evaporation of the cloud begins immediately. This evaporation cools the air within the cloud, and the mixed part of the cloud can no longer rise. Thus only the top part of the cloud continues to rise, leaving a trail behind it.

Since the mixed air is no longer rising, the thermal soon decays and grows smaller. Eventually it dies away, and the cloud begins to dissipate unless another thermal rises into the trail of the first one. Figure 18c illustrates how a cloud grows when this happens. Since the trail is a moist area, little evaporation takes place, and the second thermal rises higher than the first. The life span of a thermal is about 20 minutes, so that isolated cloudlets may form and decay quite rapidly. A wispy, fine structure is typical of cumulus clouds that are evaporating. Only if there is a continued supply of rising warm air does the cloud grow. Small clouds from isolated thermals are termed 'fair weather cumulus' or *cumulus humilis* (Plate 4). If the cloud continues to grow it may become heavy and threatening looking, in which case it is called *cumulus congestus* (Plate 5). If conditions are very favourable for continued updraughts the congestus may grow into a cumulonimbus, with the top of the cloud penetrating high into the troposphere and becoming frozen into ice crystals (Plate 6).

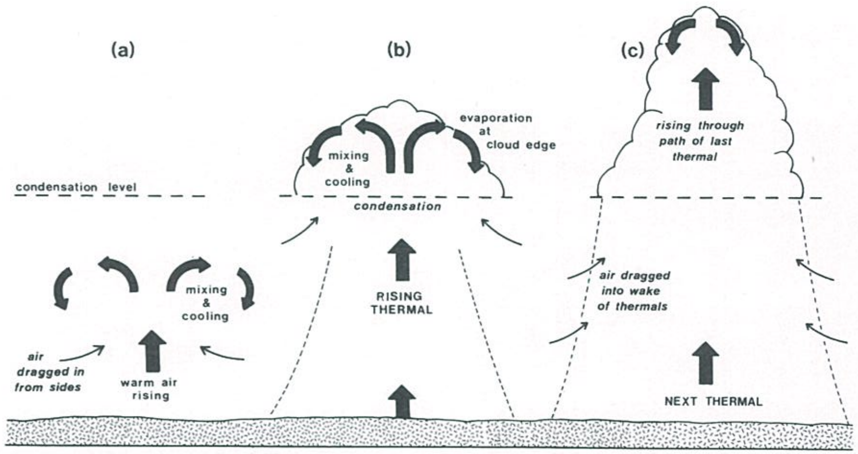


Fig. 18. Convection and the formation of cumulus cloud:

(a) Circulation in a thermal.

(b) Formation of cumulus once the rising air reaches the condensation level.

(c) If thermals continue to rise in the wake of former thermals, the cloud continues to grow.

Strong thermals may originate from forest or scrub fires, or from industrial heat sources, giving rise to isolated cumulus clouds either over or downwind of the source. When fire is the cause the resultant cloud is termed *pyrocumulus* (Plate 14).

Not all cumulus originate as thermals from ground level. If the air is very unstable thermals may start at some higher level, due to the heat released when condensation takes place. Such thermals are much smaller than ground thermals, and since they are formed in cloud, decay begins immediately. Thus tall thin cloudlets are formed, usually on a common base, giving the appearance of battlements—so that this type of cloud is called *castellanus*. Usually it is *altocumulus castellanus*, but it may also be *stratocumulus castellanus*. Such clouds indicate high level instability and may foretell thunderstorms.

Forced ascent

Air flowing over hills or mountains is lifted, and this forced orographic lifting will cause cooling and, if the air is moist enough, cloud. These clouds are often of striking and beautiful appearance, the form they take depending on the stability of the air and the strength of the flow. When the air is unstable, lifting over the hills will trigger off the convective process already described, so that showers and thunderstorms are often found over hilly country.

When the air is stable, the strength of the flow is important. In light winds, the only cloud formed may be a layer of stratiform cloud near the hill top, often referred to as hill fog. Stronger winds set up a wave-like motion in the airflow and characteristic clouds are formed—Fig. 19 shows the streamlines in an airflow over a ridge and the associated clouds. On the hill top the 'cap cloud' forms as in a light wind. Plate 15 shows a cap cloud formed by air flowing over a mountain. At higher levels *lenticular* clouds may form (Plate 8). These are stationary or nearly so, despite the strength of the wind blowing through them; they are continually forming on the upwind side in the rising air and dissipating on the downwind edge in the descending air.

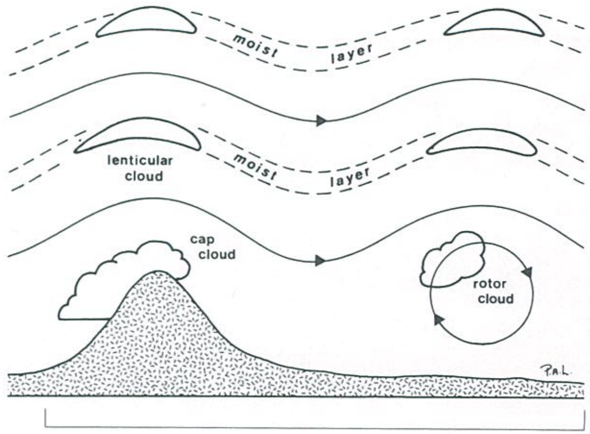
The characteristic lenticular shape is best developed when the air is fairly dry, with a relative humidity of less than about 60 per cent in the cloud environment. Several bands of these may appear downwind from the ridge on the crests of successive waves, and are referred to as 'lee-wave' clouds. Sometimes, as indicated in Fig 19, lenticular clouds may be stacked in piles, due to a layered humidity distribution.

In addition to the cap and lenticular cloud, ragged cumulus may form in turbulent eddies below the wave crests. These are called rotor clouds. They also maintain their position relative to the ground, despite the often violent turbulence within them.

A mass of air rising within a cumulus cloud will lift the air immediately above it, and a little cap of cloud may appear on the cumulus towers. This is termed 'scarf cloud' or *pileus* (Plate 16), and is usually of short duration as the cumulus tower soon penetrates it.

Near the centre of a depression, air rises slowly over an area of perhaps thousands of square kilometres. This slow lifting produces extensive sheets of layer

Fig. 19. Airflow over a mountain barrier.



clouds, which may combine to give a cloud mass several kilometres thick. Since the atmosphere is seldom uniform over a large area, release of latent heat may lead to the formation of cumulonimbus clouds embedded in such a cloud mass. Further from the centre, the lifting of warm air is concentrated along frontal zones. Where the advancing warm air glides up over colder air, great sloping cloud sheets are formed. These are several hundred kilometres across, from the first signs of cirrus progressively invading the sky, to when the heavy rain falls from nimbostratus developed as the frontal surface nears the ground. Again cumulonimbus may develop in such a cloud mass, but not commonly. Figure 20a shows the clouds commonly associated with a warm front.

Cold fronts generally give rapid lifting of a small volume of air, so that typically they are associated with cumuliform clouds, but some cold fronts do give slower, more widespread lifting, which results in the formation of layer clouds. The vertical and horizontal extent of layer clouds depends on the humidity distribution, so that uniform lifting does not necessarily lead to the formation of continuous cloud layers. The clouds associated with a typical New Zealand cold front are shown in Fig. 20b.

Advection

Warm moist air moving over a cold surface will be cooled from below, so that condensation takes place. Since this cloud is resting on the surface it is properly called fog. Over the land such fog may be dissipated by solar heating during the day, to re-form at night. Over the sea however, the diurnal change in sea surface temperature is small and the sea fog persists for long periods. Vigorous stirring by a fresh or strong wind will spread the cooling over a deeper layer, and the fog bank will then lift above the ground into a true stratus cloud layer. We can then speak of the cloud as a turbulence cloud, although it has originated by advection.

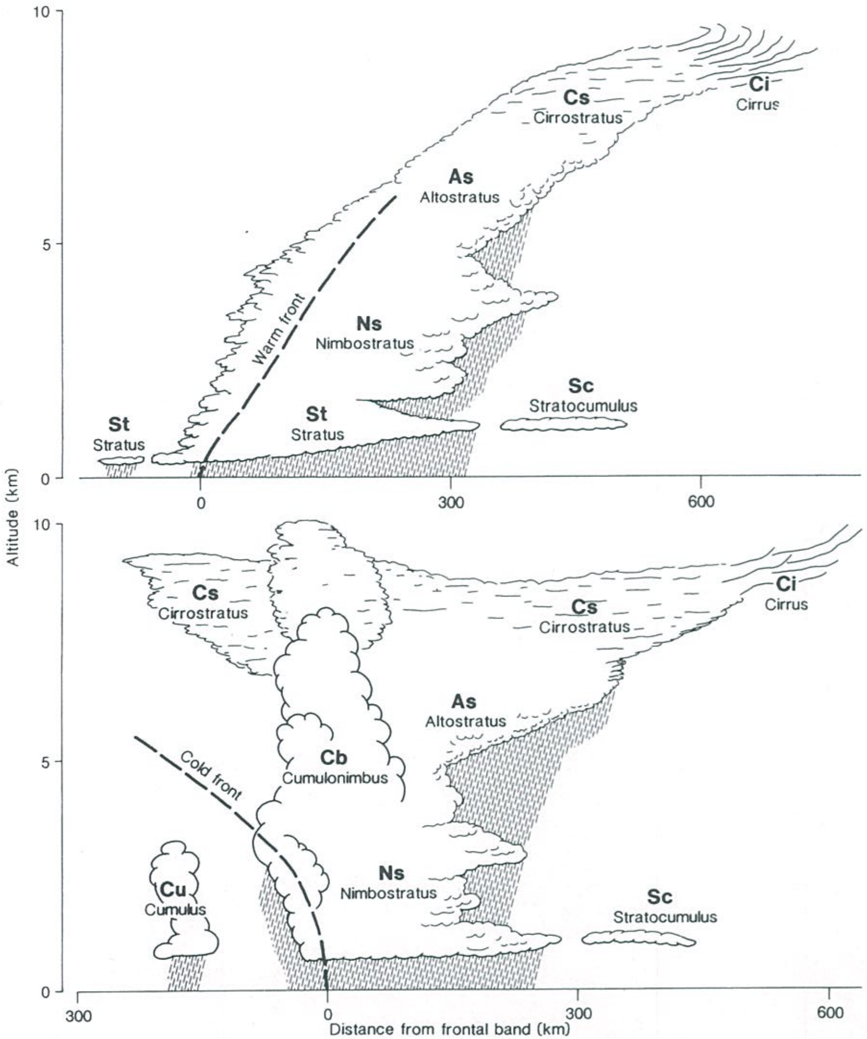


Fig. 20. Vertical cross sections through a warm front (a), and a cold front (b). Precipitation is shown by dashed lines.

Other Processes

As well as the case discussed above, other turbulence clouds may form, usually in association with an inversion. An inversion acts as a lid on vertical motion of the

atmosphere, so that turbulence is confined to the layer below the inversion. The effect of turbulence is to stir moisture evenly through the layer affected. Since the coldest temperatures will be found at the top of the layer, this is where cloud will form. Stratocumulus is a common turbulence cloud type.

Changes of wind direction, or speed, at higher altitudes give rise to local turbulence layers which are associated with altocumulus and cirrocumulus clouds. Fragmentary clouds (scud) are produced by turbulence in air moistened by rain falling through it. Another turbulence cloud already mentioned is the rotor cloud.

The mixing of moist air masses at different temperatures may lead to saturation of the mixture and hence condensation. This process is rarely important as a cloud forming process, since the temperature difference between neighbouring air masses is usually small—and there may be little mixing anyway. However it is observed on cold mornings, when wispy clouds form over relatively warm lakes or rivers. It is also observed as 'steaming' over roads or ground strongly heated by the sun after a shower. Near the edges of ice sheets this type of cloud may be extensive, where it is called 'arctic sea-smoke'.

This is also the process which leads to the formation of condensation trails from high flying aircraft, as warm moist air from aircraft engines mixes with cold moist air (Plate 13). If the cold air is nearly saturated, the trail may continue to grow across the sky, as described in the section on ice crystal clouds.

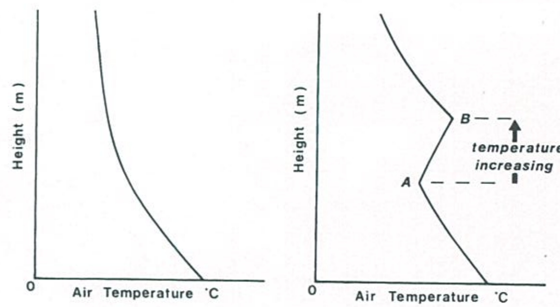
A local reduction in pressure, resulting in expansion and cooling, occurs in violent rotating motion and causes the funnel clouds of tornadoes. Over the sea, water will also rise a short distance into this vortex, and the phenomenon is known as a waterspout. Most of a waterspout is composed of cloud droplets—and not liquid water.

Local reduction of pressure also occurs just in the lee of isolated mountain peaks, especially of the 'horn' type e.g. the Matterhorn in Switzerland, or Mt Aspiring in the Southern Alps. In some circumstances a ragged patch of cloud forms

Fig. 21. Air temperature profiles.

(a) The 'normal' situation, where air temperature decreases with height above the ground.

(b) Case showing an inversion in temperature between heights A and B.



in the lee of the mountain. Vortex trails from aircraft propellers and wing-tips also result from processes of this type.

Changes in appearance

Clouds formed by any of the processes already discussed may be modified by small secondary processes, due to factors which begin inside the cloud or occur in the surrounding environment.

Normally air temperature decreases with height, but sometimes temperature inversions occur where a layer of relatively warm air lies above colder air, Fig. 21. Temperature inversions are likely to form stable layers, which act as 'lids' to upward air movement and convection. When a thermal enters a stable layer it finds itself in relatively warm surrounding air, and so it loses its buoyancy and stops rising. Figure 22 shows that when cumulus clouds reach a stable layer they cease to grow upwards, and instead the updraughts spread out at the base of that layer to form patches of cloud. These patches may persist after the decay of the parent cloud, and even combine to give a layer of cloud. If the stable layer is at low or medium levels, the cloud formed from the cumulus will be stratocumulus or altocumulus.

Continued heating from below may enable the cumulus cloud to break through the stable layer into the less stable zone above, so that cumulus congestus or cumulonimbus can develop in this association, Fig 23.

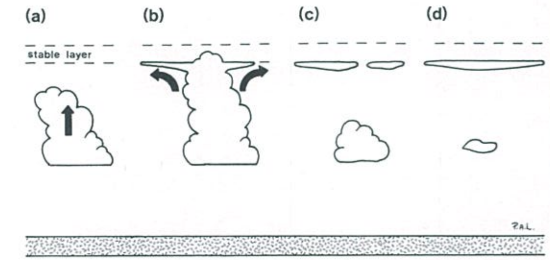


Fig 22. Spreading of cumulus at a stable layer to form stratocumulus or altocumulus:

(a) Cumulus grows by convection.

(b) A stable layer blocks upward motion, and forces the cloud to spread out.

(c) The parent cloud dissipates, leaving patches of cloud.

(d) The cloud patches combine to form a cloud layer.

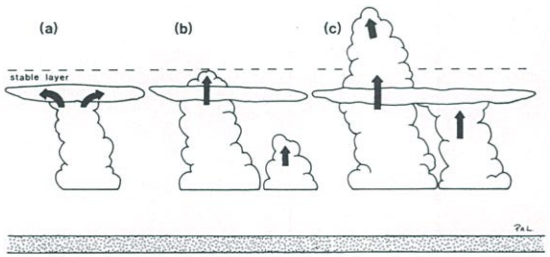


Fig. 23. Penetration of a stable layer by a large growing cumulus:

(a) Cumulus spreading out at a stable layer.

(b) Buoyant energy of some strong updraughts allows cloud tops to penetrate the stable layer.

(c) Continued heating from below allows the cloud to grow through the stable layer.

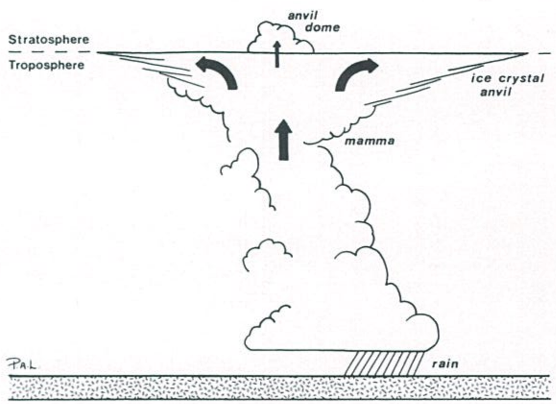
The lower boundary of the stratosphere, the tropopause, is the beginning of a very stable layer, so that cumulus clouds penetrating to this level will spread out at tropopause level. Since temperatures are always below -40°C at this level, the upper part of the cloud becomes frozen and the cumulus is transformed into a cumulonimbus. A great 'anvil' of ice crystals spreads out, giving the cumulonimbus its characteristic appearance, Fig. 24.

A layer of cloud intercepts and absorbs heat radiated from the earth, so that the base slowly becomes warmed. At the same time, the top of the layer is losing heat by radiation into space and being cooled. In such cases a slow convection may be produced in the layer, giving the cloud a dappled appearance. This is due to the evaporation of cloud in the areas where the air is sinking. All shallow layer clouds eventually assume this structure, unless there is a higher cloud layer which prevents loss of heat to space. In time the absorption of the earth's radiation may warm the cloud layer sufficiently to cause it all to evaporate.

Because of the difference between the rates of cooling of unsaturated and saturated air, air rising in clouds becomes warmer than the shallow layer of clear air immediately above it. A small scale convection process thus takes place on the cloud top, with small turrets pushing ahead of the main cloud mass. This leads to the typical cauliflower-like upper surface of developing cumulus.

Similarly air which is sinking in cloud, warms less rapidly than the layer of air immediately below it, and this colder air sinks down in small udder-like protuberances called *mamma*. Mixing soon takes place with the clear air and the proturberances tend to evaporate, but if they contain rain or snow they may persist for longer and become quite large and heavy looking. Such areas of descending cloud are found on the under-side of the overhanging anvil of cumulonimbus and on the under-side of wave clouds.

Fig. 24. Cumulonimbus, cloud, and associated features.



Cumulus which penetrates high into the troposphere eventually reaches a region where temperatures become so low, that most of the water drops freeze into ice crystals. This process, known as 'glaciation', changes the former crisp bubbly look of the growing cumulus into a silky smooth-looking cloud. These ice crystal tops may persist for a long period after the parent cumulonimbus has evaporated, and the cloud is then called 'anvil cirrus'.

Wind structure plays an important part in determining cloud forms. The wind almost invariably changes with height, either in direction or speed, or both. These vertical changes affect cloud forms by distortion or arrangement.

When the wind increases with height, the top part of clouds which extend over a deep layer, will move faster than the bottom part. Thus cumulus towers are often tilted, while ice crystal trails often lag behind their parent clouds in smooth curves. Changes of wind direction with height will also twist these trails into erratic forms.

Arrangement of clouds by wind can be of several forms, such as long lines of cumulus clouds stretching downwind from hills or islands, or long streams of ice crystals extending downwind from a parent cloud. The pattern of globules or rolls of altocumulus, cirrocumulus and stratocumulus are also due to arrangement by the wind—in this case the clouds are associated with abrupt changes of wind with height. The direction of the wind's *change in direction* with height determines the arrangement, with the billows or globules lying at right angles to this direction. When the wind speed increases strongly with height with little change of direction, the billows lie nearly at right angles to the wind direction; when the winds are comparatively light, the billows take on different directions in different parts of the sky.

Dissipation

Just as clouds are formed by cooling of the atmosphere, so then are they evaporated by warming. This warming may be due to sinking of the air, mixing with clear air, or by direct heating.

As air descends it is compressed and this warms it, so that regions of subsidence are regions of clearing skies. Vast areas of subsidence are found in anticyclones, while smaller areas occur in the vicinity of cumuliform clouds. Descending air is also found on the downwind side of wave crests. One well known example of this is the nor'west arch of Canterbury, where sinking air gives a clear sky in the immediate lee of the ranges, before the air rises again into the main cloud sheet.

Saturated air mixing with drier air, as in the vicinity of cumulus tops, leads to evaporation of the cloud droplets. Such evaporation cools the air and it begins to sink. Sinking warms the air, and further evaporation takes place. This process is easily observed in dissipating cumulus. Increased turbulence may mix a cloud layer with drier air above and cause it to all evaporate. This is another example of the mixing process.

Convection carries heat from the ground to higher levels, and throughout the

day this heat may be enough to raise the temperature of all air in the layer to above the saturation point. The cloud base tends to rise during the day, and may reach the level of the tops—this is the stage when all the cloud evaporates.

A layer of cloud at high or medium levels will radiate heat both out into space and down towards the earth. If there is a lower layer, then it will absorb earth radiation and cloud radiation, which may be sufficient to evaporate it in time.

The processes discussed here are the ones which determine the shape and form of a given cloud. However it is rare to find only one of these processes acting at a given time—rather, the state of the sky at any given time is likely to be due to a combination of several of these processes of growth, modification, or decay. Only careful observation and study of the changing sky, will enable the observer to extract all the available information from the clues so randomly scattered.

Plate 1. Stratus

Hanmer. A fairly uniform, featureless, grey layer of low cloud, which produces little, if any, rain. Billows rising from the top of the cloud are due to weak convection.

A. A. Neale

Plate 2. Fog

Wellington. Stratus cloud that touches the ground is known as fog.

N.Z. Met. Serv.

Plate 3. Stratocumulus

Wellington. A low grey layer cloud which is often lumpy in appearance or composed of rounded masses or rolls.

R. W. Heine

Plate 4. Cumulus humilis (*humilis*—low, of small size)

Small fine weather clouds formed by convection. They have little vertical development, and are relatively short-lived.

N.Z. Met. Serv.

Plate 5. Cumulus congestus (*congestus*—heaped up)

Wigram, Christchurch. Clouds showing strong vertical development.

R. M. Smith

Plate 6. Cumulonimbus

Hawkes Bay. Heavy and dense cloud with considerable vertical extent, with a smooth flattened anvil-shaped top.

A. J. B. John

Plate 7. Altocumulus stratiformis undulatus (*stratiformis*—flat layer; *undulatus*—having waves)

Christchurch. Altocumulus clouds are middle level clouds, either white or grey, and generally with shading.

R. A. Crowder

Plate 8. Altocumulus lenticularis (*lenticularis*—lens shaped)

Wellington. Middle level clouds, most often of orographic origin where a mountain range forces air upwards.

N.Z. Met. Serv.

Plate 9. Nimbostratus

Wellington. Grey dark cloud layer, thick enough to block out the sun. Brings more or less continuous rain, which reaches the ground.

R. M. Smith

Plate 10. Cirrus uncinus (*uncinus*—hooked)

White, silky clouds made of ice crystals. In the form shown, with strands and hooks, sometimes referred to as mares' tails.

N.Z. Met. Serv.

Plate 11. Cirrus fibratus (*fibratus*—threadlike)

Straight or irregularly curved filaments or threads, which do not end in hooks or tuffs. (This example is var. *vertebratus*.)

N.Z. Met. Serv.

Plate 12. Cirrocumulus stratiformis undulatus

Hawkes Bay. The cirrocumulus cloud is the high cloud shown in the example (the lower cloud is cumulus *mediocris*). Cirrocumulus has no shading, and is composed of very small separate elements.

A. J. B. John