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CLOUD FORMS

The following notes have been prepared by Mr R.M. Smith for use in lecturing to aircrew trainees. As they may be of wider interest they are reproduced for general information.

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CLOUD FORMS

1. INTRODUCTION

The importance of a study of cloud forms, structure and development cannot be overemphasised. Clouds make visible those stirrings of the atmosphere which are of utmost importance to the airman, for on those air movements his comfort and, at times, his safety depend. Sometimes they merely show present conditions, but at other times they foretell the future. The study is also a rewarding one; there are many beautiful cloudscapes for those who observe and appreciate them.

2. FORMS 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 upcurrents. Once formed, the cloud may be altered by internal movements which will be described later.

3. CLASSIFICATION OF CLOUDS

An internationally agreed nomenclature is based on the three basic cloud forms. This nomenclature is fundamentally the one proposed in 1803 by Luke Howard, a London pharmacist. He proposed the names :

STRATUS	(Latin = layer)	for sheet cloud,
CUMULUS	(Latin = pile)	for heap cloud,
CIRRUS	(Latin = hair)	for streak cloud.

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 designate clouds in the middle troposphere. Thus there are now recognised 10 main cloud types :

CIRRUS	Ci	=	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 heaped cloud

In addition, varieties of these clouds are distinguished by such names as "lenticularis" for a lens shaped cloud and "castellanus" for a cloud showing a thin turreted appearance. Various features of the fine structure may also be defined e.g. "mamma" for udder-like protuberances on the under side of a cloud.

4. 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 mb for every 30 feet. Thus air which is rising is subject to reduced pressure and expands. 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. Thus unsaturated air always cools at 3°C per 1000' 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 releases latent heat, which serves partly to warm the rising air. Below about 10000' this warming is sufficient to reduce the rate of cooling to about half the dry adiabatic lapse rate i.e. to 1.5°C per 1000'. At higher levels (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 the 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, 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 at the same rate at the same time. Thus one part of it 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. The 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.

5. ICE CRYSTAL CLOUDS

Although temperatures near the ground may be quite high, the 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 5-10000' in winter and 10-15000' in summer. Thus many clouds occur in these sub-freezing regions and we might expect them to be composed of ice crystals. However, this is not necessarily the case.

Condensing vapour rarely, if ever, produces ice crystals directly. Above a temperature of about $-40^{\circ}C$ water droplets are always formed, of which only a few subsequently freeze to ice crystals. However, below $-40^{\circ}C$ 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 they soon become much larger than the droplets, possible 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 onto 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.

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.

The direction of fall of the snow crystals will often show variation in wind with height, the parent cloud often moving ahead of the trail.

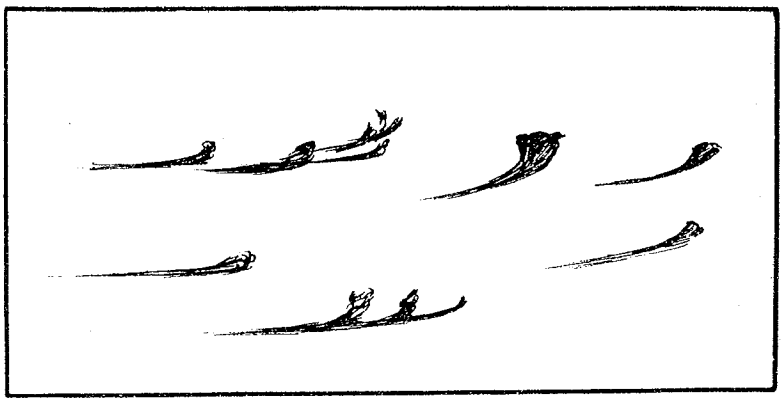


Fig.1. Cirrus clouds with ice crystal trails.

6. PROCESSES OF CLOUD FORMATION

6.1. Convection

6.1.1. 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 the dragging of air into the base (known as entrainment) the thermal grows bigger as it rises. This kind of motion can be studied in the smoke emitted from railway engines when conditions are relatively calm.

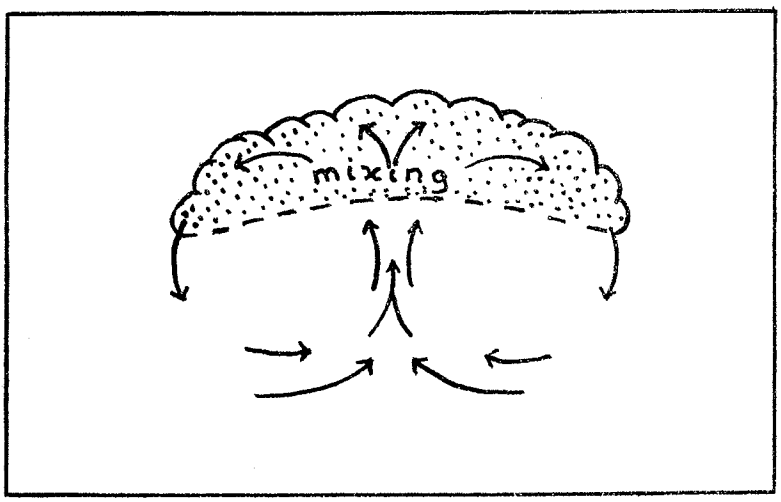
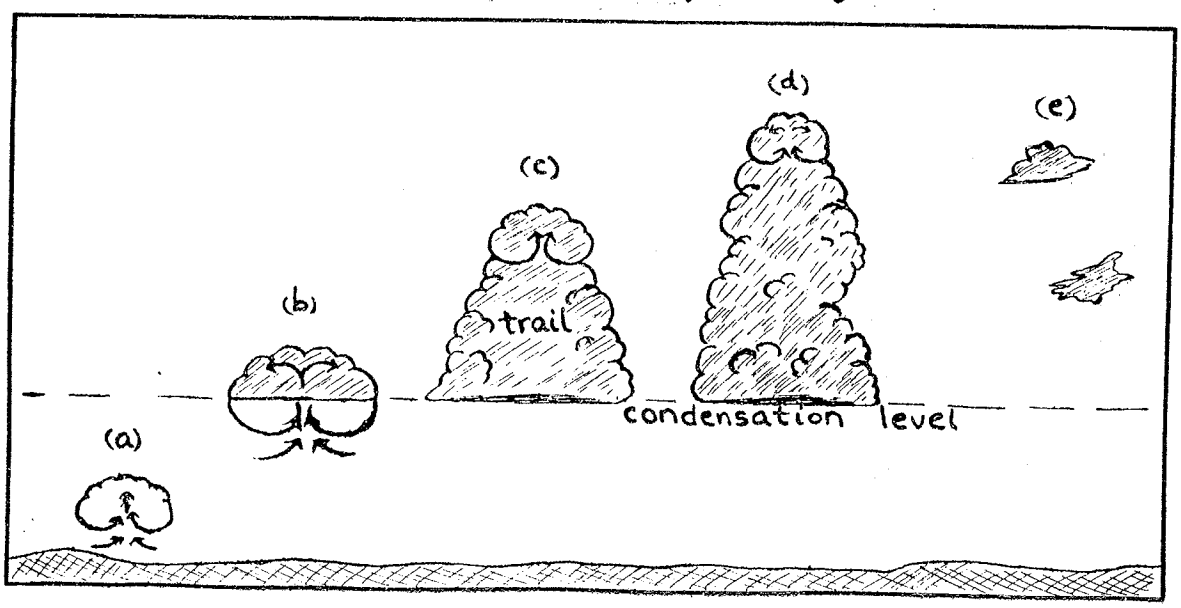


Fig.2. The circulation in a thermal.

When a thermal reaches the condensation level it becomes visible as a cumulus cloud. A bulging cauliflower - like top is produced by the 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. If this happens, little evaporation takes place, since the trail is a moist area, and the second thermal rises higher. The life span of a thermal is about 20 minutes so that isolated cloudlets may form and decay quite rapidly. Only if there is a continued supply of rising air (warm) does the cloud grow. Small clouds from isolated thermals are termed "fair weather cumulus" or cumulus humilis. If the cloud continues to grow it may become heavy and threatening looking, in which case it is called cumulus congestus. 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. The growth of a thermal into a cumulus cloud is shown in Figure 3, from the initial stage (a) and first penetration above the condensation level by the expanding bubble (b) through the growth of the trail (c & d) to the final dissipation (e). Note that the condensation level is horizontal, so that although there are turbulent stirrings below the cloud, the base of it is quite flat. A wispy, fine structure is typical of cumulus clouds which are evaporating.

6.1.2. 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 of condensation released in cloud formed by passage of air over a hill. These 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. This gives the appearance of battlements so that this type of cloud is called "castellanus". Usually it is altocumulus castellanus, but may also be stratocumulus castellanus. Such clouds indicate high level instability and may foretell thunderstorms.

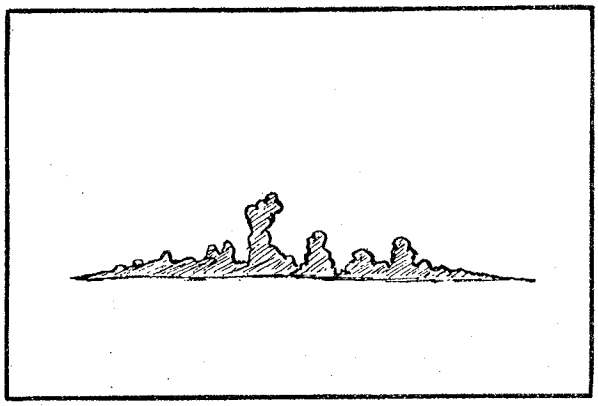


Fig.4. Castellanus.

6.2. Forced Ascent

6.2.1. Orographic Lifting

Air flowing over hills or mountains will be lifted, and this forced lifting will cause cooling and, if the air is moist enough, cloud. These clouds are often of striking and beautiful appearance. The form of the clouds depends 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. This is often referred to as hill fog. Stronger winds set up a wave like motion in the airflow and characteristic clouds are formed.

In figure 5 are shown the streamlines in an airflow over a ridge and the clouds associated with such a flow.

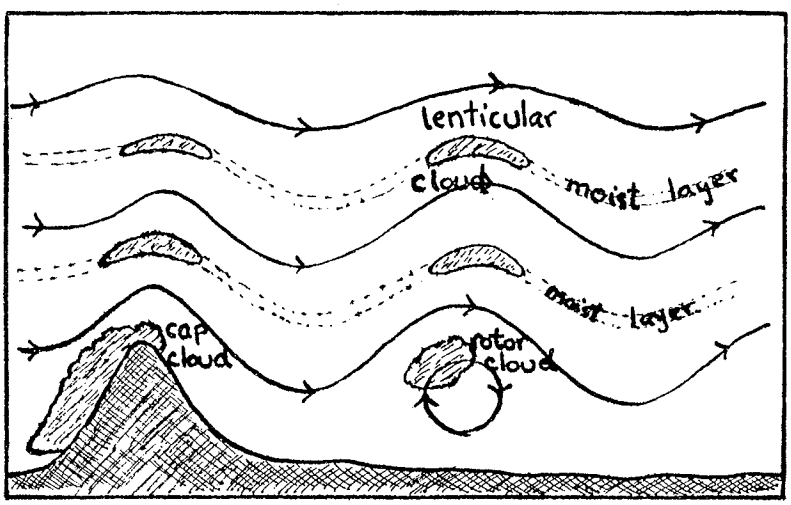


Fig.5. Airflow over a ridge.

On the hill top the "cap cloud" forms as with a light wind, while at higher levels lenticular clouds form. 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% in the cloud environment. Several bands of these may appear downwind from the ridge on the crests of successive waves. Sometimes these lenticulars may be stacked in piles, due to a layered humidity distribution.

If the air is very moist the lenticulars may combine into a continuous sheet of cloud, as appears over Canterbury in northwest conditions.

In addition to the cap cloud and lenticulars, 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.

6.2.2. 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, and is usually of short duration as the cumulus tower soon penetrates it.

6.3. Ascent over a wide area

Near the centre of a depression air rises slowly over an area of perhaps thousands of square miles. This slow lifting produces extensive sheets of layer clouds which may combine to give a cloud mass many thousands of feet thick. Since the atmosphere is seldom uniform in its characteristics 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 miles across, from the first signs of cirrus progressively invading the sky to the time of cessation of the heavy rain from nimbostratus which develops as the frontal surface nears the ground. Again cumulonimbus may develop in such a cloud mass, but not commonly.

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 a uniform lifting does not necessarily lead to the formation of continuous cloud layers.

6.4. 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 reform 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 lifts above the ground into a true cloud layer. We may then speak of the cloud as a turbulence cloud although it has originated by advection.

6.5. Turbulence

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 will be 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 with which are associated altocumulus and cirrocumulus.

Fragmentary clouds ("scud") are produced by turbulence in air moistened by rain falling through it.

Another turbulence cloud already mentioned is the rotor cloud associated with orographic waves.

6.6. Mixing of air at different temperatures

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 or there may be little mixing. 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; here 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. If the cold air is nearly saturated, the trail may continue to grow, as described in section 5.

6.7. Local reduction of pressure

A local reduction in pressure, resulting in expansion and cooling, occurs in violent rotating motion and causes the funnel clouds of tornadoes. Over the seas, water will also rise a short distance into tnis 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 in the lee of the mountain. This is often called "smoking mountain".

Vortex trails from aircraft result from processes of this type.

7. PROCESSES WHICH CHANGE THE APPEARANCE OF CLOUDS

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 which are occurring in its environment.

7.1. Spreading at inversions or stable layers

When cumulus clouds reach a stable layer their vertical motion is stopped and the updraughts spread out at the base of the 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 so formed from the cumulus will be stratocumulus or altocumulus. (see Fig. 6.)

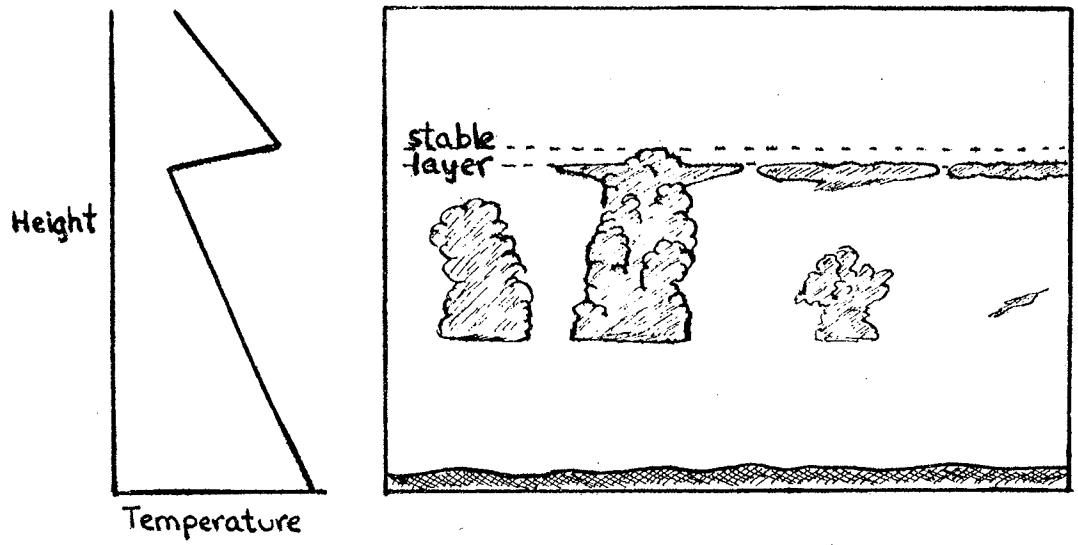


Fig.6. The development of a layer of cloud from the spreading of cumulus at a stable layer.

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. (see Figure 7.)

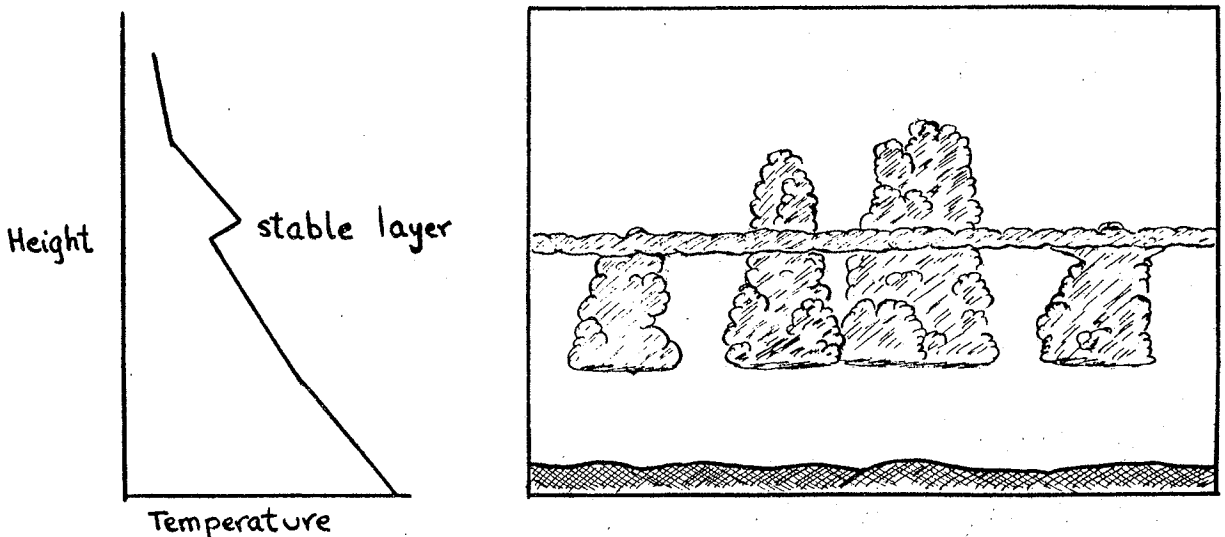


Fig. 7. Penetration of a stable layer by strong cumulus.

The lower boundary of the stratosphere 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. (Figure 8).

7.2. Convective processes not due to thermals

7.2.1. Convection may be released in cloud formed by the passage of air over a hill, as for example, when the air is stable for unsaturated air but unstable for air which is saturated. In such cases cloud due to orographic lifting or widespread ascent may appear identical with cloud due to thermal convection. These clouds have been discussed in sections 6.1.2, 6.2.1 and 6.3.

7.2.2. Small scale convection in layer cloud.

A layer of cloud intercepts and absorbs heat radiated from the earth so that the base becomes slowly warmed. At the same time, the top of the layer is losing heat by radiation into space and is 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.

7.2.3. Small scale convection in rising or descending cloud.

Because of the difference between the rates of cooling of unsaturated air and saturated air, air rising in clouds becomes warmer than the shallow layer of clear air immediately above it. Thus a small scale convection process 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.

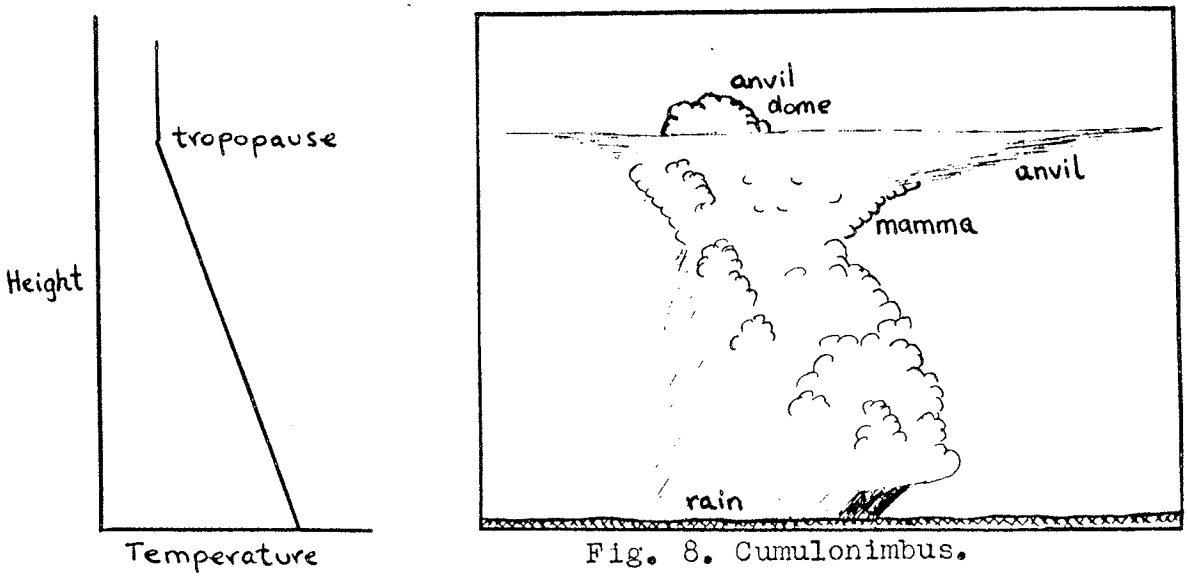


Fig. 8. Cumulonimbus.

Similarly, air which is sinking in cloud warms less rapidly than the layer of air immediately below it. This cold air sinks down in small udder - like protuberances ("mamma"). Mixing soon takes place with the clear air and the protuberances 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 underside of the overhanging anvil of cumulonimbus, and on the underside of wave clouds.

7.3. Glaciation

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. The cloud is then called "anvil cirrus".

7.4. Changes due to wind

Wind structure plays an important part in determining cloud forms. The wind almost invariably changes with height and these changes may be in direction, or speed, or both. These vertical changes in the wind field affect cloud forms by distortion (7.4.1.) or arrangement (7.4.2.)

7.4.1. Distortion

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.

7.4.2. Arrangement

Arrangement of clouds by wind can be of several forms. Thus we find 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 wind shear determines the arrangement, with the billows or globules lying across this direction. When the wind speed increases strongly with height without much change of direction the billows lie nearly at right angles to their direction of motion. When the winds are comparatively light, small local changes affect the direction of wind shear to a large degree and the billows take on different directions in different parts of the sky.

8. DISSIPATION OF CLOUDS

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

8.1. Subsidence

As air descends, it is compressed and is warmed by this compression. Thus regions of subsidence are regions of clearing skies. Vast areas of subsidence are found in anti-cyclones, while smaller areas occur in the vicinity of cumuliform clouds. Descending air is also found on the downwind side of wave crests. One example of this is the famous 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.

8.2. Mixing

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.

8.3. Direct Warming

Convection carries heat from the ground to higher levels and throughout the day this heat may be enough to raise the temperature of all the air in the layer to above saturation point. Cloud base tends to rise during the day and may reach the level of the tops, 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. Thus, if there is a lower layer, it will receive earth and cloud radiation, which may be sufficient to evaporate it in time.

9. CONCLUSION

The processes discussed above 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 moment 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 airman to extract all the available information from the clues so randomly scattered.

10. ACKNOWLEDGEMENTS

Much of the above material has been based on the writings of F.H. Ludlam and R.S. Scorer and for a more complete treatment of the subject the following references may be consulted.

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