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Convection in the atmosphere

By F. H. LUDLAM and R. S. SCORER
Imperial College, London

CONTENTS

1. THE PROCESS OF CONVECTION

Motion in the atmosphere originates almost entirely through the action of gravity on masses of air that are differently heated. At the one extreme is the motion of the pressure systems and at the other is the small-scale stirring motion, usually called turbulence, which very largely originates through the degeneration of motion of a larger scale. In between is the overturning motion in which the vertical velocities are comparable with the horizontal ones. This kind of motion, which is therefore restricted to dimensions not greatly exceeding the depth of the troposphere, is our main concern. We shall not deal with the synoptic situations in which this overturning occurs, nor with the results except in so far as they affect the motion itself, but we shall see how far this complicated process can be comprehended in simple terms.

The fundamental idea of buoyancy was clearly understood by Archimedes (*c.* 220 B.C.), and although the formulation of Newton's laws of motion made it possible for the science of hydrodynamics to advance enormously, the study of convection has lagged far behind. There are even signs that it might be split into two parts, on the one hand *hydrostatics* and on the other *turbulence*, and most of the concepts used in thinking about convection have been derived from one or other of these. An exception to this is the study of *convection cells*. Most of the work on this aspect of convection has been described by Brunt (1937 and 1939) who gave to Bénard the credit for having first recognized cellular motion and studied it seriously. Since 1939, treatments of convection cells have tended to become irrelevant to the motion in the atmosphere.

Since glider pilots began in the 1920's to develop the art of *thermal soaring* they have been, somewhat unwittingly, the chief source of information about the nature of convection currents, and powered aircraft, in spite of their ability to carry instruments and go to any chosen position, have not yet outstripped gliders as a means to discover more about thermals. If the emphasis of effort in aviation had been on ability to remain airborne rather than on speed and independence of the weather, there would undoubtedly be aircraft in existence today which would be ideal for meteorological exploration. As it is, a convection cloud is regarded by aviators as a sometimes hazardous region of bumpiness and possible icing rather than of interesting and helpful motions.

The study of heated jets attracted much attention in the 1940's, particularly in connection with fog dispersal, and had much influence on meteorological thought, particularly in America which was far from the birthplace of thermal soaring in Germany. Finally, the atomic bomb cloud has provided some ideas on the subject, but it can scarcely be said that it demonstrates anything relevant to our problem that cannot be seen in ordinary cumulus clouds.

Because there has so far been no synthesis, and some contradictions of viewpoint have arisen from these various lunges into the field from one side or the other, our chief aim is to present a unified picture of what happens during the process of convection. We shall not discuss the complications which arise when precipitation is formed inside convective clouds.

2. Slow convection

2.1 *Cellular patterns*

Convection occurring in a cellular pattern has been extensively studied on account of its relative simplicity. The pattern is stationary and the motion steady. The mathematical theory has been concerned with a layer of gas confined between two rigid conducting surfaces or with a shallow layer of liquid. The purpose of the theory has been to find the shape of cell that occurs most easily, and it has been assumed that the temperature gradient through the layer is uniform and is slowly increased until convection begins, and that then the transport of heat is maintained at the minimum required to keep the motion going. Acceleration of the motion is prevented by the molecular viscosity which destroys shear and by the molecular conductivity which destroys horizontal temperature gradients produced by the motion.

Laboratory studies by Walker and others (described by Brunt) have been concerned with the same conditions and the cells have been rendered visible by smoke in gas or metallic dust in liquid. It has been possible by applying a relative horizontal motion to the bounding surfaces of the gas or by having a wind across the liquid surface to arrange the cells in a rectangular pattern or to distort the cells into longitudinal or transverse rolls. Jeffreys (1928) suggested that longitudinal rolls, in which the direction of rotation in adjacent rolls is opposed, were to be expected; but the transverse ones, all with the same direction of rotation, can be obtained with small amounts of shear. A hexagonal or rectangular pattern can be obtained with no shear.

In the atmosphere, altocumulus formations are strikingly similar in appearance to these laboratory patterns, but there are many differences. If the motion were confined between two almost horizontal surfaces a layer of cloud would appear at the top, and not the separate cloudlets which are observed. One possibility is that the upper or lower surface of the overturning layer is not horizontal and that the cloudlets are in thicker parts. It is evident that in the atmosphere no difference in density comparable with that at the upper surface of a liquid will occur and that the inertia of the overturning fluid cannot be neglected, as it is in the theory, particularly since the restraints of viscosity and conductivity are so much less. Theory and experiment are not in accord concerning the humps and hollows on the upper surface of an overturning liquid (Jeffreys 1951), but the problem with no sharp density discontinuities has not been tackled theoretically and this discord has therefore not arisen in the atmospheric case.

The instability in the atmosphere can arise in a variety of ways, but it is unlikely that a uniform temperature gradient will be slowly established through a cloud layer. It is more probable that the instability will arise at the upper or lower surface of a cloud layer if a general lifting or sinking of the air occurs. In this case, unless the whole depth of the cloud is involved in the overturning and the other surface acts as a sharp limit to the convection, there will be no definite length characteristic of the defining circumstances of the motion and so no characteristic cell size will appear. Indeed, most altocumulus does not possess a uniform cell size. When shear occurs, variations in the depth of the overturning layer will be inhibited and a definite cell size will appear at the same time as regular formations.

The molecular viscosity and conductivity play a vital role in the theory and in laboratory experiments. They enable a uniform temperature gradient to be gradually established, and prevent accelerations when the overturning begins. There is no equally effective agent in the atmosphere where molecular influences are negligible and eddy viscosity and conductivity do not become effective until the motion occurs. The molecular effects also determine the direction of motion within the cells, which in a gas is downwards in the centre and in a liquid upwards. This is said to be because viscosity increases with temperature in a gas, but decreases in a liquid. It is, however, possible that the direction of motion is also greatly influenced by the weight of suspended particles used to make the motion visible, and is predominantly upward in gases containing heavy smoke because of this. The motion in clouds appears to be predominantly upwards in the middle of the cells because cloud lumps are more common, and though reticular (netlike) clouds do appear, it cannot be concluded from their appearance that downward motion in the middle is producing the evaporation of the cloud, for the holes may be due to the perforation of the cloud layer by a clear layer below.

If we examine the atmosphere to see if anywhere the conditions of the theory and laboratory experiments might be more nearly approached than in altocumulus cloud, the region of the NE. Trades seems a likely place. The air is moving steadily towards warmer sea so that heat is being put in slowly at the bottom and the motion is often limited at the top by a sharp inversion. Woodcock and Wyman (1947) claim that cellular convection does occur there but the evidence is suggestive rather than compelling, and the motion is not, for the reasons given, completely analogous to that discussed in the theory and observed in the laboratory.

The complication due to condensation has not been considered : cloud has merely been treated as an indicator of the motion. It is possible that the overturning is ' once for all ' and that the cloud lumps are the air masses that have ascended (or descended if the layer is penetrated by clear air from below in reticular fashion). This obviates the difficulty that steady cellular motion produces a cloud layer, but the real nature of the motion can only be discovered by a more careful examination of the clouds themselves than has yet been undertaken.

2.2 *Billows*

The longitudinal rolls which seem most likely to occur according to laboratory experiment and theory have not been definitely observed, except possibly in cloud streets (to be discussed later), whereas transverse rolls are common in clouds. If the motion is not ' once for all,' but overturning continues, then the appearance of gaps between the rolls suggests the heaping together of a layer into the rolls. If this were once effected then it has been shown (Scorer 1951) that the configuration can be described mathematically, the billow-like structure being perpetuated by wavy motion above and below the overturning layer. The amount of shear that exists does not affect the spacing of the billows which depends only on the depth of the layer overturned. The theory only applies strictly to infinitely long rolls and when there is an unending row of them.

The dynamical effect of the wavy motion in the air above and below seems to have the effect of spreading the regularity of spacing beyond the region where the instability originally began. Thus if a patch of cloud becomes unstable and forms billows, further billows often appear in clear air with the same spacing. The shear propagates the influence and the cloud forms first over the centre of the billows so as to extend the pattern : the condensation provides the energy for the overturning in the rolls and then billows proper are formed; the influence is then spread further into the clear air.

It seems to be a property of shear that it can propagate regularity of spacing once it has begun. If in one region regularly spaced clouds appear because there is some characteristic length in the defining conditions, such as spacing of heat sources or depth of layer overturned, then the spacing is propagated by a dynamical influence which induces further convection to assume the same spacing in places where there is no characteristic length. Though the depth of a cloud layer, or some similar depth, might be the origin of the spacing to begin with, in patches of cloud the spacing does not alter towards the edge, where the cloud is presumably thinner, and, as just mentioned, it is propagated into clear air.

The phenomenon of billows is not the same as that of cellular altocumulus where the cell size does seem to vary more readily, but there are cloud formations which cannot be obviously put into either category.

2.3 *Mammatus clouds*

These are clouds in which the motion is certainly downwards in the centre of the units. Masses of cloud sink into the clear air below and usually have a smooth rounded outline. The best examples occur in the environs of large cumulonimbus clouds where cloudy air may ascend rapidly and spread out over the top of drier air and then sinking of the whole mass occurs. The cloudy air then warms less rapidly and descends in drop-like masses into the clear air below. The clear air from below often ascends in a similar manner in between the descending masses and can produce very light channels in an otherwise very dark cloud mass. The life of each drop is of the order of 3 min and there is generally no regular pattern. The under side of stratocumulus-cumulogenitus displays the same phenomenon though less well developed.

Another mechanism for obtaining more liquid water in the lowest regions of a cloud than if the air that is directly beneath ascended into it, is for larger droplets to fall from higher levels in the cloud. This has been suggested by Wagner (1948) as a mechanism for lowering the base of the cloud when the whole air mass subsides or for saturating and cooling the air immediately below cloud base by evaporation of the falling drops. If the precipitation continued it would then be contained in air that was denser than that immediately below it.

When a large area of precipitation is generated quickly, as for instance on the under side of an overhanging anvil-like part of a vigorous cumulonimbus, the outline of the cloud is often the lower boundary of a region containing precipitation. The base of this precipitation descends, and is usually well inclined to the horizontal, and the effective density of the air containing the precipitation is greater than that of the clear air. The base then generates a mammatus formation.

Drop-like formations also occur frequently in condensation trails. If the growth of the crystals in them is rapid enough to increase sufficiently the effective density of the air containing them before the trail is dispersed, the trail breaks up into pendulous lumps. This property of disintegration of a horizontal ' tube ' of fluid of different density from its surroundings can be demonstrated by introducing a fine jet, composed of water weighted and made visible by potassium permanganate or other dye, into a stream of water. The trail of ice crystals formed in a cold box in the laboratory along the trajectory of a pellet of ' dry ice ' through a fog of supercooled water droplets gathers into sinking lumps in the same way.

Regular geometrical patterns are not a characteristic of areas of mammatus cloud even though the size of the drops is restricted to a small range. One is led to consider whether their size is determined not by a length in the defining conditions but by the rate at which fluid is supplied to the drops. Rate of heating plays no part in the theory of convection cells and in the laboratory one is concerned to make it as small as possible while still effective. When the rate of supply of buoyant fluid is important we begin to formulate the concept of an environment through which it shall rise, and are led to consider the properties of these penetrating masses.

3. THEORIES OF THERMALS

We are concerned in this section with ascending currents, usually called *thermals*, and how they are imagined to originate and behave. There is certainly no general theory of convection but ideas have grown up round special problems. The theory of *heated jets* expounded by Schmidt (1941) showed how the temperature anomaly, vertical velocity and width of the jet could, for an isolated point or line source of heat, be expressed as powers of the height above the source. The method of solution was derived from the study of boundary layers and turbulent wakes of cylinders and has likewise been applied to convection over a uniformly heated plane surface by Sutton (1948). Though he claimed observational support for his power-law solutions, and thought in terms of bubbles mixing with their surroundings, Sutton would deduce no physical picture of the processes of convection from his analysis, except, of course, that the scale of motion was also proportional to some power of the height.

The chief idea imported from the theory of jets is that mixing takes place between the jet and its surroundings, but the existence of the mixing is a hypothesis or is at least regarded as a property of fluids, and is not explained. The result of the mixing is to decrease the buoyancy by dilution and to increase the mass of ascending air, and the consequent steady increase in upward momentum is equal to the buoyancy and no accelerations can therefore occur. For this kind of flow to occur in the atmosphere a continuous intense solitary source of heat must be provided, and the eruption of Vesuvius in 1944 provided a good example on calm days. Slater (1939) describes how several sailplanes soared in the cone of warm air (on a calm day) from the chimney of a cement works. Such instances are, however, exceptional.

Because sailplanes were often able to remain in an upcurrent for as much as 20 min, during which time they sank between 1,000 and 1,300 m through the air although the region in which they were able to ascend was often less than one third of this width, the thermals were imagined to be ascending columns of air, sometimes described as 'chimneys.' Sometimes it was thought that the air did accelerate upwards because the upcurrents were found to be weaker closer to the ground. Equally they were usually less broad low down and the widening could be ascribed to mixing, as in a jet. Thermals were imagined to be coming from some 'hot spot' or part of the ground which was able to supply more heat to the air than the neighbourhood. This idea of thermals as 'chimneys' has predominantly, though not exclusively, found favour in America.

The pioneers of thermal soaring in Germany (see Pielsticker 1940) were probably more influenced by the remarkable smoothness of thermals. Since on many occasions the entry into a thermal was sudden they were likened to bubbles of warm air ascending, with no mixing of importance, up to the equilibrium level where they flattened out horizontally. The belief that mixing was unimportant is well exemplified by Höhndorf's claim (1947) to have seen once, under special circumstances, a bubble overshoot the equilibrium level, which was near the condensation level, and sink back below it again, making as many as eight complete oscillations before vanishing. It was well known that the lapse rate near the ground was superadiabatic and it was imagined that the relative uniformity of the earth's surface produced nearly horizontal isotherms so that though unstable the air was in equilibrium. If the equilibrium were disturbed by the slope of the ground, the presence of a 'hot spot,' or the sudden descent of a cold mass from above with a consequent scooping effect, a bubble of warm air from the superadiabatic layer where the isotherms were humped up would ascend and be replaced by colder air which would remain at the ground for some time before becoming hot enough to ascend. A 'hot spot' or hump would therefore send up a series of bubbles, and many attempts have been made to measure the frequency with which they were released, but with no evident success. It seems that, if this picture be accepted, a chain of bubbles is released in quick succession followed by a long pause with no release.

The bubble model has found its most general acceptance in Europe, but its inadequacies are plain even to soaring pilots who make use of it because of the great variety of sizes and bumpy regions around them. They have been imagined to be elongated to various degrees according to experience of them.

Bubbles which mix into the surrounding air have been considered by Taylor (unpublished) and Sutton (1947). They considered spheres of very hot air but have rather assumed a symmetrical kind of mixing than tried to describe the mixing process, and have applied their idea chiefly to the hot mass of air generated by the atomic bomb. The appearance of the mushroom-shaped top of the cloud produced by it has suggested a kind of turbulent vortex ring or spherical vortex, and the idea of applying such a model to ordinary thermals has found adherents.

A theory, more simple because it offers a single unit of convection to explain all the phenomena, more complex because of the varied behaviour of the unit in combination with other units, has been proposed by Scorer and Ludlam (1953). Though hot spots play their part they are not an essential requirement, while the superadiabatic layer is not regarded as a clear-cut layer but as quite indefinite in extent. Their bubble model has a sharply defined upper cap at which mixing into the surroundings begins through the static instability there. Further down it merges almost imperceptibly into a wake which is a mixture of the bubble with the surroundings through which it has passed. The bubble is rapidly wasted away and only ascends about twice its original diameter before it is completely mixed into its wake. The wake is then, for a short time, a region where ascent of further bubbles to greater heights is preferred. The amalgamation of wakes of small bubbles into larger bubbles goes on continuously as long as the supply is kept up. If the supply lapses a fresh growth must begin by the ascent of bubbles into unprepared air.

In this way the increase of the size of thermals with height is explained. The superadiabatic layer is the region of amalgamation of the smaller, less efficient, bubbles and wakes into larger ones; and when a larger one begins to ascend it is replaced at the ground by a mass of cold air from above. The convergence often observed at the ground towards the point of ascent of a bubble is of cold air to replace it, and this cold air does not itself follow the bubble up. At this point the wake plays an important role. It is a region of turbulent stresses, the stirring motion being due to the horizontal gradients of density, not of velocity in the first instance. These stresses nullify the minimum of pressure found immediately beneath a warm bubble, and so no organized horizontal convergence occurs below a bubble, except at the ground when it first leaves. Certainly no significant pressure minimum is to be expected beneath a cloud.

Because bubbles are rapidly wasted away when ascending along a path not recently travelled by other bubbles, most do not reach the equilibrium level for air ascending unmixed from the ground, but the height reached by thermals depends on the supply of heat to a region where agglomeration of bubbles is taking place.

4. Effects of wind shear

There is no documentation of observations which makes the testing of a theory possible. This is because the phenomenon of convection is so influenced by the nature of the locality (as described below) and the features of the weather special to the day, such as cloud amount, synoptic situation, time of year, condition of the ground and so on, that no such thing as typical convection occurs. Naturally, therefore, the theories have grown up around the experience of those formulating them and give a good qualitative explanation of what the authors each regard as the most significant observations. No theory is at present precise enough to make predictions of upcurrent strength or dimensions but some sort of prediction is possible in the case of thermals ascending in a shearing current.

Malkus (1949b), using the idea of the thermal ‘ chimney ’ into which surrounding air was mixed, computed how the mixing into the jet caused it to move horizontally as it ascended into surroundings moving with a different velocity. The most important result was that the air of the thermal in a shearing airstream moves with a velocity measurably different from that of the surroundings. Hitherto relative horizontal motion had not been seriously considered. This result was taken into account in computing the slope of a cloud, but the observations are not accurate enough nor the slope of a cloud steady enough for any real test to be made of the theory, particularly because arbitrary assumptions about the level at which the updraught originated were also necessary. In principle the amount of mixing was deduced from observations on the ascent of the thermal, but in a rather roundabout way because the vertical velocities and amounts of dilution were unfortunately not measured for the clouds whose slope was observed. Scorer and Ludlam obtained a rough estimate of the ratio of the relative horizontal velocity to the vertical velocity, which again indicated that it should be measurable.

At the same time glider pilots have observed that often, when thermals are entered suddenly, an instantaneous increase in airspeed occurs. This has been rather dubiously explained in terms of the aerodynamic reactions of the glider on entering an upcurrent, but since no forward acceleration is sensed by the pilot it is reasonable to attribute it to a genuine relative horizontal motion of the air of the thermal. According to Malkus's theory there is no reason why a decrease should not just as often be observed. Nor, according to a ' chimney ' theory in which mixing is important, is a thermal likely to be entered suddenly but would be bounded by a bumpy region.

In a shearing current clouds are observed to grow mainly on the up-shear side (which is usually the upwind side), and dissipate on the downwind side. Malkus explains this, in a manner not readily understood, as being due to the displacement of the upcurrent into the shear and thereby predicts the upcurrents to lie outside the cloud on the up-shear side. Such upcurrents have been observed by glider pilots. Clouds appear to grow into the shear by succeeding turrets ascending on the up-shear side. Since ordinarily shear is in the wind direction this may be due to the source of the thermals being fixed to the ground or at any rate to the lower layers of the air. The bubble theory explains this as due to the displacement in the down-shear direction of the top of the region of bubble building of which the cloud is evidence : succeeding bubbles ascending through the lower part of the region inevitably appear on the up-shear side.

Because of the relative horizontal velocity, the wakes slant down the direction of shear from the bubble cap, so that a glider, if it enters the thermal through the cap, as it must in order to do so suddenly, must enter from the up-shear side. At the same time the evaporation and the consequent downcurrents (described below) lie almost entirely on the down-shear side according to either theory, and this would compel almost all gliders to enter the thermal from the up-shear side, and thus observe an increase of airspeed, but this explanation does not apply well below cloud base where the phenomenon is most often observed, nor would the thermal be entered suddenly. Circulations within the thermal bubble could also affect the change in airspeed if the thermal were entered suddenly.

A rotation about a vertical axis would have the same effect if the thermal were entered obliquely against the rotation. If entered with the rotation no lift would be observed because of the decrease in airspeed and so the thermal would not be noticed as being entered suddenly. On the other hand a column rotating with a sudden decrease in moment outwards is an unstable configuration so that this explanation is inadequate.

The upcurrents in the clear air on the up-shear side are thought to be in the air rising above fresh bubbles ascending beneath. It is well known that pileus clouds are often formed in this way, and, as just mentioned, the fresh bubbles do appear on that side.

The bubble theory of Scorer and Ludlam stresses the importance of the cap of the bubble, for this is the only clearly identifiable part of the velocity and temperature fields that compose it. The rest of the field is deduced from it. The chimney idea emphasizes the properties of the flanks of the region of rising air. If this latter picture be accepted the air that is cooled (pileus cloud for instance) above a rising bubble might be observed to be simultaneously rising and colder than the surroundings and interpreted as a special kind of thermal so far admitted on no theory except in this way. This illustrates the danger of deducing from random traverses by aircraft a relationship between upcurrent and temperature anomaly. Because of the unknown velocity distribution in the wake similar paradoxes could appear there. The great value of the exploration by sailplane of a single thermal from top to bottom cannot be too much stressed.

5. Thermal sources

An upcurrent will persist only so long as fresh bubbles continue to enter it. A good thermal source is a piece of ground from which bubbles can ascend for longer without a break than in the neighbourhood.

One possibility is for warm air to be accumulated in among buildings, trees or standing ripe corn, to be released in large quantities when a gust of cold air sweeps across and displaces the warm air. In the case of ripe corn or buildings the solid surfaces in contact with the air become a great deal hotter than green vegetation because none is used to evaporate moisture taken in by the roots. A large tree may transpire as much as three tons of water on a hot day.

Thermal sources may be places where the surface achieves a higher temperature in the sunshine. Besides green vegetation a surface of wet clay soil, which keeps cool by evaporation, may be a cool region whereas bare rock or sand achieves a higher temperature. The temperature achieved is not the only consideration for a surface that can continue to warm the air even when a shadow passes over it will provide a good source : concrete runways, areas of bare rock, or buildings and roads seem to do this. Though generally woods and forests are cool during most of the day, German soaring pilots report that air trapped among the trees produces thermals after the rest of the ground has begun to cool in the evening.

If a cool region lies downwind of a warm region thermals appear to be released at the downwind edge of the warm area. The idea is that the sharp horizontal gradient of temperature close to the ground causes the cool air to undercut the warm. Some pilots have reported finding thermals a mile or two out to sea when the general wind is offshore. When a shallow sea breeze is blowing these thermals are almost continuous and produce elongated cumulus clouds stretching out to sea from the highest points on the land. Other places where there is a temperature contrast at the surface, such as the edge of a wood or lake, or marked change in vegetation, are also said to be good sources.

The most powerful sources are undoubtedly provided by high ground. The heat is put in higher up and on slopes a horizontal temperature gradient is automatically produced. The first convection clouds of the day almost invariably appear over hills and anabatic winds feed them, and as we shall see in Section 6, convection is often prevented over the lower ground by sinking motion, so that throughout the day clouds may appear only over the mountains. Over the mountains of Spain large cumulus clouds tower upwards, covering large areas of the sky with their anvils, while almost no cumulus appear over the plains and valleys. Langmuir (1950) describes the same phenomenon in Honduras where the clouds over the mountains ‘ pump cirrus ’ into the sky.

Davies (1951) has described the almost continuous ascent of air over a ridge in Derbyshire. On that occasion the general wind was light and along the ridge, while near the ground the drift was towards the ridge. The lower layers were heated by small bubbles and then moved anabatically up the slope.

It is often found that over the lowlands around York thermals are weak and cannot support a glider while the jurassic limestone and chalk escarpments of east and south-east England provide good upcurrents. This has been ascribed (Douglas 1943) to the nature of the soil, clay and carboniferous types respectively, but is more probably due to the latter being outcrop escarpments and good thermal sources for that reason.

Nothing of value is known about the temperature distribution over the sea when convection is taking place, but the temperature is unlikely to be appreciably reduced and is rather maintained by stirring when cool patches of air descend to the surface. Circulations within the sea make its thermal capacity effectively infinite, and thermals will grow in competition with each other, the width and spacing of them being determined by the amount of heat being transported upwards.

6. TYPES OF MOTION

6.1 *Streets*

Clouds are often found arranged in rows called *cloud streets*. According to Welch (1953) dry thermals behave similarly. This has been explained as cellular motion arranged as longitudinal rolls by the shear, and although the analogy is difficult to explain, Scorer (1952c) has suggested that as in other cellular motions an orderly arrangement may only occur when the heating is only just sufficient to maintain the convection. Cumulus clouds arranged in a rectangular pattern over wide plains or over the sea are sometimes seen, and the same condition is probably present. Isolated streets are often seen lying downwind from good thermal sources or along feeble fronts when rain is falling from them. Because thermals grow into shear, if any exists, streets will not lie exactly down the wind direction at the surface.

6.2 *Rotation of thermals*

If the surface contains no good thermal sources as, for instance, when it has a very small thermal capacity or is almost uniform, or both, like a sandy desert, the supply of thermals to the same volume is not kept up and no larger bubbles can be created. Under these circumstances the lapse rate increases to that appropriate to the transport of heat by small bubbles only and becomes superadiabatic up to 3-4,000 ft (Flower 1936), or perhaps higher. If rotation about a vertical axis can be produced the air may become organized into a *dust devil*. The necessary spin is created where the surface wind is retarded by the huts of a village or the trees of an oasis or at one end of a small ridge or embankment across the wind, and, as many writers have pointed out, is intensified by convergence. Flower infers that the lapse rate must be superadiabatic up to at least as high as dust devils are seen to ascend, and Swinn (1953) has soared to 7,200 ft in one in Egypt.

The rotation enables the rotating mass to ascend without disintegration. Rayleigh (1916) pointed out that if the moment of the momentum about the axis increases outwards the variable centrifugal force has the same effect as a stable stratification of density, and so mixing with the surroundings or wasting by mixing as with a bubble would be inhibited. Any mixing would tend to reduce the spin in the middle in such a way as to produce a stable configuration. This could equally well be caused by friction at the ground when the spin is produced by convergence of the air set in rotation by a mechanism such as that just suggested, and it may be noted in this connection that the air that is rotating contains dust drawn up from the ground. The friction at the ground therefore seems to be essential to the production of this kind of thermal.

If the convergence continued right to the centre with no friction the spin would become infinite. Or, if the column were drawn out vertically through being surrounded at all levels by denser air, the spin would be greatly increased and the pressure enormously reduced in the centre. In many, and possibly in all dust devils, the central core consists of air drawn at the top into this low-pressure region. Since the free air is not rotating, as is the air coming up from the layer influenced by non-uniform surface roughness, it can enter the core without acquiring an enormous spin. The air is unstable at all levels for downward as well as for upward displacements and so the core is usually colder and descending. If the supply of rotating air at the ground is cut off the truncated column often continues to ascend to a height of several thousand feet. Dust devils have been described also by Ives (1947). Swinn has made some remarkable flights in them by glider.

Moving dust devils usually follow a path curved to the right or left according as their rotation is anticlockwise or clockwise when viewed from above. This may be because the air most retarded by friction at the surface is on the side where the velocity is greatest, and this air feeds the more central part because it has less vorticity and will therefore be stably situated if surrounded by the rest of the air that ascends.

As would be expected the earth's rotation appears to have no effect on the direction of rotation.

Waterspouts do not originate at the surface but generally within a vigorous cloud. The pressure minimum beneath a warm bubble usually extends only a small distance below it because of the stresses in the disturbed motion of the wake. As we shall see below, the lapse rate in the air above cloud base usually exceeds the wet adiabatic, and to an extent depending partly upon the rate of heat transport. In regions where convection is extremely vigorous, as over the ocean in a polar-air depression, the lapse rate may be such as to form large bubbles very rapidly. There are no turbulent stresses until the bubble has ascended and undergone some mixing and so if the air beneath it possesses some rotation, as it well may in among vigorous up and down motions present in neighbouring thermals, it will converge into the low-pressure region below the newly-formed bubble with very little stirring. In this way a rapid rotation and a very low central pressure are induced, and again, since the cause of the low pressure is not a bubble which has ascended through the air, the air further down is subjected to similar convergence and the spout extends down to the surface. Whether the cloudy air in the centre actually originates in the cloud or not is not known. At the sea surface a copious spray is produced, probably as the wind blows over waves produced by the rapid fluctuations of pressure as the spout moves.

Tornadoes are a similar phenomenon but are much less common because the land does not usually supply heat rapidly enough over a large region for the lapse rate above cloud base to be sufficiently steep for the very rapid creation there of large bubbles. The air that converges under large bubbles leaving the ground is necessarily colder and from above the bubble base and remains at the ground, while the bubble ascends and forms a turbulent wake. Rotation does not therefore usually occur under ordinary thermals at any stage.

Koschmieder (1951) has described the formation of funnel clouds over an intense heat source provided by a stream of lava.

Tropical hurricanes, about which there is a considerable literature, are mentioned here only to remark that, in common with dust devils, they appear to develop where the air is positively unstable, not simply not stable, over a considerable depth, in this case for saturated air, and that descending motion occurs in the middle. The air in the eye is, however, warmer, not colder than the surrounding air, perhaps because it has descended from the stratosphere. According to Bergeron (1949) hurricanes die out in passing over land not because of the convergence made possible by friction but because the heat source, the sea, on which its continuance depends has been removed.

6.3 *Downcurrents and sonic disturbances*

No theory so far described makes any definite prediction about where the downcurrents occur to compensate for the thermals. Isolated jets are presumed to produce no down-motion except at infinity, though some might be expected if many heat sources were distributed over a very wide (infinite) area. The only limit to the distance from the thermal at which the down-motion can occur is placed by the maximum atmospheric signal velocity. This is equal to the velocity of sound at some level in the atmosphere, and a thermal of duration 20 min cannot be compensated for by downcurrents more than 360 km away, but if a region of convection lasts several hours the distance of the sinking motion may be many times this. Koschmieder (1940) says that the sinking occurs at a great distance and, as we shall see, this may often be a condition to be fulfilled before convection can persist while at other times it is the result of the convection and enables it to continue.

The expansion which results from air being heated is made possible (Scorer 1952a) by the outward movement of the surrounding air as a sonic disturbance passes outward from the heated region, and the result is that for practical purposes the density of the heated air is immediately lowered and the pressure beneath it falls as a result. The air above is lifted initially but pressure gradients at high levels are smoothed out by a sonic disturbance of a type similar to the Krakatoa air wave or the semi-diurnal pressure wave. It has been argued (e.g., Bleeker and Andre 1950, Sawyer 1949) that when a volume of air is heated the isobaric surfaces above are lifted and so an outflow at high levels occurs; the pressure is then said to fall at the surface and an inflow begins there, and because this inflow is impeded by friction at the surface the pressure deficit is not made up and a region of low surface pressure results. Bleeker (1950) even asserts that if it were not for friction all pressure gradients at the surface would be greatly reduced by inflow there. The origin of this error is not clear. It is in contradiction to the observed filling up of depressions as they move over land where, it could equally be argued, friction makes flow inwards across the isobars possible. Sutcliffe and Forsdyke (1950, p. 202) have even suggested that pressure gradients are usually less at the surface than higher up because of the influence of the boundary, probably through friction.

Since the outflow from a heated region is by means of a sonic disturbance which results from an external source of energy the compensating rise in pressure may be distributed anywhere a sonic disturbance can reach, and with the speed of sound. After the pressure has thereby been re-distributed the convective motion begins. It is of a different type because it results from the operation of a conservative field of force and converts potential energy into kinetic. The sonic disturbance results from the application of an impulse to the air by the increase in pressure that results when air is heated without expansion and the pulse travels through the air and produces a slight displacement.

In view of what follows it seems to us unprofitable to discuss the downcurrents apart from the motion on a much larger scale than the individual thermals. To understand this it is necessary to describe the mechanism whereby convection warms the air. In cloudless air a thermal must either mix with its surroundings or spread out at its equilibrium level, and in either case only the regions reached by the thermal air itself are warmed. The sinking motion in the surroundings produces no local warming because the air is not stably stratified – otherwise there would be no considerable convection. In order to warm a layer over ground that is more or less uniformly heated, thermals must ascend more or less everywhere and infuse their heat into the whole mass. Above the condensation level heat is temporarily borrowed which enables the ascent of the thermals through a stably stratified environment. The sinking motion therein warms it. Thus it is possible for a whole mass of air to be warmed by convection clouds occurring in only a small part of it. It is seen below that the actual air of the cloud thermals does not diffuse heat into the surroundings by mixing.

If clouds occur, therefore, since the air between them is warmed more efficiently than the air into which they ascend they will continue to ascend in the same place. Cumulus clouds situated throughout the day only over the higher mountains of a country such as Spain provide a mechanism for warming the whole mass of air above the condensation level, below which the heating is achieved mainly by widespread dry thermals. This idea has been confirmed by the experiences of glider pilots (Scorer 1952b). The adiabatic layer is fed towards the cloudy regions by anabatic winds.

The circulations set up in this way must have some inertia and probably overshoot the equilibrium state when convection ceases in the evening. The subsequent swing back in the opposite direction may be a dominant cause of the reversed circulations observed at night, though katabatic winds play their part. Clearly a quantitative study of this process is desirable. The convection of a day seems to have a considerable influence on the convection of the succeeding night, while the day seems to be relatively unaffected by the convection of the preceding night (Scorer 1952b). This is understandable if it is the inertia of the daytime circulation that is largely responsible for the nocturnal circulation in the opposite direction : the oscillation being damped shows little tendency to persist into the next day, and it is not renovated by thermals from the surface at night.

Because of the possibility of warming the whole air mass by means of a few clouds, streets of clouds can continue to warm the whole mass, whereas streets of clear-air thermals are probably less persistent.

We return therefore to envisaging a circulation on a scale larger than the individual convection clouds which resembles the cellular convection which we have discarded as an interpretation of the thermals themselves. In the case of cloud-street formations the cell size has been reduced almost to the size of the average cloud bubble. If a larger scale circulation exists, the convection in the region of convergence and general ascent is more vigorous than cloud-street convection.

Some attempts have been made to fit all other forms of convection to the cellular model. Durst (1932) drew an analogy with the 'horseshoe' pattern assumed by cells in shallow liquid over the top surface of which a wind blows. The columns in the centres of the cells are pushed over to one side at the top surface. The sudden gusts of cold air observed as thermals pass were identified with the edges of the cells which now have almost a discontinuity at the points to which their centres have been pushed. Albrecht (1942) presents a somewhat similar picture, based however on a bubble concept, of thermals being released by the scooping effect of a micro-cold front. This effect undoubtedy occurs at the downdraughts produced by cumulonimbus (Suckstorff 1938), but in the absence of precipitation it seems unlikely that the cold gusts originate higher up than just above the adiabatic layer. They are a necessary part of the process of the beginning of ascent of a large bubble, rather than the cause of it. Just as the most important feature of a bubble is the discontinuity of the temperature at its cap, so the lower surface of a descending cold bubble is well defined and a sudden arrival of cold air at the ground occurs. The generation of these discontinuities within a previously homogeneous fluid has not been properly explained. The equations of motion are non-linear, and the explanation of the progressive accentuation of gradients is bound to present difficulties.

6.4 *Sea breezes*

Using relaxation methods at each time step of a progressive integration of the equations for the case of air originally stagnant across a coastline when the land is heated, Pearce (1952) achieved some success in demonstrating the production of a front at the surface. Such fronts do occur (e.g., Peters 1938) but have not been satisfactorily explained in any published treatment of the sea-breeze problem. Some simplification is necessary because all factors together produce a problem of intolerable complexity. The difference in mechanism of heat transfer over the land and sea, the difference in stability (there is no adiabatic layer over the sea), the 'Eulerian' acceleration, the earth's rotation, any already existing drift of air and the transfer of momentum by thermals – these are the chief sources of difficulty. In simplifying the mathematics by assuming a solution with a daily period an unreal difficulty is encountered, for infinite terms appear in the equations at 30° latitude when the earth's rotation is allowed for. Because the sea breezes there are not catastrophic the assumption of interminable repetition must be abandoned and the problem complicated in consequence.

It cannot be said that any treatment of sea breezes is satisfactory. Most are considered to be commendable if they reproduce the well-known characteristics of actual sea breezes which have long been explained in the most simple terms, and such results are by no means the monopoly of any particular model. Perhaps because it is thought easy to explain sea breezes they have scarcely been accorded the attention they deserve, for almost all features of convection that we have described can play their part to varying degrees in their establishment.

7. CUMULUS CLOUDS

In small thermals which barely reach the condensation level ragged *fractocumulus* forms, with no clearly defined base. From the ground larger clouds appear to have well-defined level bases at a uniform height, but from close at hand it may be difficult to define the level of the cloud base to within a hundred feet, and variations considerably greater than this are sometimes found within a few miles. According to glider pilots the base of a large cloud may be a few hundred feet higher than the general level, over a limited area where a strong updraught occurs, so that this part of the cloud base is raised in a dome-like impression (Scorer and Ludlam 1952). The glider pilot ascending in this hollow can see the ground beneath some time after the horizons have been obscured. This might be due merely to the differing lengths along the lines of sight which are within cloud when the pilot is just above a uniform base, but this explanation does not usually satisfy those who observe the phenomenon. At other times the base is found to be lower where the updraught is greatest.

Above the level of the cloud base the lapse rate in the clear air becomes less than the dry adiabatic, but usually is at first considerably greater than the wet adiabatic, so that the temperature excess of the thermal bubbles inside the clouds, and their buoyancy, may increase. The buoyancy of the cloud air is proportional to the excess of virtual temperature, less a correction to take into account the weight of the condensed water. At temperatures below -10°C the virtual temperature is practically the actual temperature, but with a constant clear-air humidity the difference increases until at 10°C it may often be 1°C greater than the actual temperature. The buoyancy due to an excess of 1°C, which is the order of that usually found, is just nullified by a condensed-water concentration of about 3·5 g/kg of air, a value which may commonly be exceeded inside large clouds. Both corrections to the excess of actual temperature must therefore be taken into account in estimating the buoyancy of cloud air, particularly at the higher temperatures.

7.1 *The adiabatic rise of cloud air*

The *parcel theory* of cumulus growth, due mainly to Refsdal (1930) and Normand (1946) assumes that the cloud air rises through an undisturbed clear-air environment, so that on an indicator diagram its temperature at any level lies on the saturated adiabatic which passes through the point representing the cloud base (Fig. 1). If the condition of the clear air as revealed by a sounding is plotted on the diagram, the excess of virtual temperature and the buoyancy of the cloud air at any level can readily be determined.

According to the theory the cloud air accelerates upwards while the buoyancy is positive, attaining a maximum speed at the *equilibrium level* (Fig. 1) and then decelerating under a negative buoyancy until its kinetic energy is expended. In practice it has become customary to expect the ascent to cease a little distance above the equilibrium level, but even so forecasters often noticed that cumulus tops were limited to much below this level, and felt the need for an improved theory which would give a more reliable estimate of the size attained by the clouds.

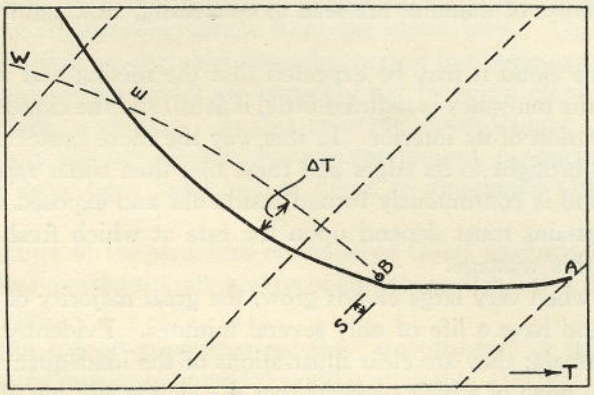

Figure 1. Typical features of the state of the atmosphere during cumulus convection, as shown on a tephigram. The thick line shows a sounding, with a superadiabatic lapse rate near the ground (A). The point B represents conditions at the cloud base, and the pecked line BW is a wet-adiabatic intersecting the sounding at E, the 'equilibrium level.' The maximum possible temperature excess ΔT inside the clouds is that between the sounding and the wet-adiabatic. In a shallow layer S just below the level of the cloud base the lapse rate may be noticeably less than the dry adiabatic. This layer has been called the 'sub-cloud layer.'

An attempt to provide one was made by Petterssen, who, following Bjerknes (1938), supposed that warming of the clear air between the cloudy updraughts, due to a compensatory settling, diminished their temperature excess and the energy liberated inside the clouds. He suggested (Petterssen *et al.* 1945) that the cloud tops were to be expected only a little above the level at which the lapse rate in the clear air first becomes equal to the saturated adiabatic (Fig. 1). The reasoning behind this suggestion is not clear, for the effect he considers only diminishes the buoyancy of the cloud air, and near the cloud tops the fraction of the sky occupied by ascending clouds becomes so small that the simple parcel theory should be equally applicable. The statistics presented in support of this suggestion are not convincing, although they confirm that the parcel theory often greatly overestimates the cloud growth.

The equation of continuity, which these writers use to demonstrate the necessity for compensating sink between the cloud updraughts, does not show where or over what extent the sink will occur. Several writers have suggested that it may be distributed over such a wide area, extending beyond the region of convection, that its effects are inappreciable. Our subsequent discussion shows that it is not profitable to consider it apart from other large-scale vertical motions.

The essential feature of the cumulus convection which these simple theories overlook is the continuous mixing and evaporation of cloud into clear air. Recently studies of cumulus growth have been concentrated upon the effects of this mixing.

7.2 *The effect of mixing on cumulus structure*

At the edges of a cumulus the mixing of the cloud into the clear air is accompanied by the evaporation of cloud particles and a chilling whose magnitude depends upon the quantity of water evaporated, the humidity of the clear air and the initial temperature excess of the cloud air. With the clear-air humidities ordinarily encountered (between 50 per cent and 80 per cent) and a temperature excess of 1°C, the evaporation of liquid-water concentrations exceeding $\frac{1}{2}$ g/kg of air involves the mixing of the cloud air with about 0·5 to 5 times its volume of clear air, and causes a chilling of between 1°C and 2°C. This chilling is usually sufficient to produce a negative buoyancy, and consequently the details on the flanks of cumulus are seen to be sinking, although the cloud as a whole may be growing.

Well inside the cloud it may be expected that the mixing and its effects are much less pronounced : the buoyancy is reduced little, if at all, and the cloud grows in pyramidal shape by the protrusion of its interior. In this way the more protected internal parts of the cloud are soon brought to its edges and they, too, then suffer rapid mixing with the clear air. The cloud is continuously turned inside out and exposed to evaporation, and the size which it attains must depend upon the rate at which fresh thermals enter its base to overcome this wastage.

Even on days when very large clouds grow, the great majority of the cumulus reach only a small size and have a life of only several minutes. Evidently they represent the rise of isolated thermals; they are clear illustrations of the inadequacy of former theories of cumulus growth, none of which suggests that the clouds will not all grow to the same size.

Stommel (1947) drew attention to observations of trade-wind cumulus which showed that their tops are generally much below the level which cloud air could reach if it rose adiabatically from the cloud base. He assumed that by some mechanism clear air was incorporated or ' entrained ' into the cloud updraught, causing the evaporation of some of the condensed water and a substantial reduction of the temperature excess. Subsequently a number of American writers have discussed the effects of such an ' entrainment '; their work has been reviewed by Malkus (1952). Apart from emphasizing the importance of mixing processes during cumulus growth, the theories of ' entrainment ' have not so far been useful, for they have been based on the concept of the uniform mixing of arbitrary proportions of clear air into the cloud updraught, and the bare hypothesis that mixing occurs has led to no explanation of how it is caused.

7.3 *The structure of large cumulus*

It seems essential to construct some physical model of the mixing of clear air into clouds. Scorer and Ludlam (1953) have attempted this. They observe that large cumulus clouds exhibit a succession of prominences having a characteristic diameter of about a kilometre and identify these with individual bubbles which ascend through the cloud base as thermals, or which may be assembled within the cloud. They propose that in general such bubbles have a maximum diameter of rather less than 2 km, and that large cumulus are composed of a number of bubbles and of their wakes, in which there is a vigorous mixing with the surroundings (clear air or other wakes).

Small clouds less than about 2 km deep contain only one or two thermal bubbles. A large volume of clear air is mixed into the wakes of these bubbles, and the rate at which the cloud turns inside out is such that the inner parts can rise a distance only about equal to the horizontal extent of the cloud before being halted by exposure to mixing with the clear air. A large cloud can be built up only by the rise of numbers of thermals in close succession, and must normally have roughly the same pyramidal shape. Those thermal bubbles which rise near the edges of the cloud mass suffer the most severely from mixing with the clear air and are halted the soonest. The wakes of these bubbles are mixed into the wakes of bubbles which rise nearer the middle of the cloud : here the dilution with clear air is less, and the bubbles are able to ascend farther, eventually emerging to form the cloud tops, but in this way some of the clear air is mixed even into the middle of the cloud mass.

As the ascent of thermals occurs irregularly the large cloud has a chaotic structure. It may consist largely of bubble wakes, in which the temperature may be lower than that of the outside air and the concentration of condensed water only a small fraction of the value corresponding to adiabatic ascent from the cloud base. The buoyancy of large volumes may be negative, so that downdraughts occur; but these can produce only small vertical displacements of air which are certainly not to below cloud base unless falling precipitation maintains a chilling. In this case the downdraught can be maintained, and often in thundery weather extends down to the ground, producing squalls and other phenomena which have been described in detail by Suckstorff (1938) and Byers and Braham (1949).

This latest picture of the structure of the large cloud accounts for the observations made inside them by powered aircraft, and reconciles these with rather different impressions gained by glider pilots.

The glider pilot has often emphasized the ' smoothness ' of the air flow which he finds while being lifted rapidly in powerful cloud updraughts, and that ' bumpy ' conditions are characteristic only of the edges of updraughts (see, e.g., Wichmann 1948). He has been inclined to discount the idea of updraught air being mixed with clear air in any degree, since to be effective over the width of an updraught during its lifetime (over perhaps a kilometre within 15 min) it would be associated with turbulence on a scale to which his aircraft is sensitive. However, he takes measures to stay in the interior of rising bubbles, and it is understandable that he should find the air ' bumpy ' only when he leaves the updraught or when it begins to fail.

On the other hand the pilot of the powered aircraft makes a rapid horizontal traverse of the cloud. He passes through chaotic bubble wakes and perhaps one or two bubble centres, experiencing a bumpy succession of variable up- and down-draughts.

The glider is well suited to exploring those parts of the large clouds, the bubble centres, which are of greatest interest. Within these bubbles the condensed-water concentration and the updraught attain their maximum values, so that they are the seats of rain and hail formation, severe aircraft icing and thunderstorm-electricity generation. The powered aircraft encounters these regions only by chance, and then passes through them in a few seconds at a speed which makes the recognition of hydrometeors and the measurement of liquid-water concentration and temperature difficult and uncertain. The measurements made in such flights must be interpreted with great care; it must be considered that mostly they refer to conditions in bubble wakes, and that no definite relations are likely to exist between the details found on successive traverses of a cloud separated by intervals of several minutes.

Accurate observations of temperatures are particularly difficult to make at high airspeeds because of the uncertain correction for kinetic heating of the thermometer element in cloudy air. When the conventional dry-adiabatic correction appropriate in clear air is made to the indicated thermometer readings, cloud temperatures are usually deduced to be lower than the clear-air temperatures at the same levels, so that the cloud air appears to have a negative buoyancy. Almost certainly, however, the reduction of the indicated temperatures should be less by an amount depending upon the droplet concentration in the air, for as the droplets approach the thermometer bulb they are not subject to an adiabatic warming; rather, they wet the thermometer element and there is some evaporation. Errors of two or three degrees Centigrade might in this way enter the deduced temperatures. However, the observations made by the aircraft of the Thunderstorm Project (Byers and Braham 1949) showed that the air inside growing cumulus possessed a positive temperature excess of up to about 4°C, while negative temperature excesses of about the same amount occurred in the downdraughts of mature thunderclouds. There was a clear relation between the temperature excess and the draught speed, the high excesses being associated with average speeds of about 10 m/sec.

Recently Byers (1952) has published the detailed analysis of one of these thundercloud traverses, in which he states that a moist-adiabatic correction for kinetic heating at the thermometer element has proved to be the proper one inside ' wet ' clouds, although it is not wholly reliable. This implies that the element is wet and indicates the wet-bulb temperature of the air passing over it. In the example he describes the dry-adiabatic correction led to the temperatures observed at 20,000 ft inside a thunderstorm appearing rather lower than those outside, but in fact the region of strong updraught (about 12 m/sec) was associated with a temperature excess of 5°C.

Warner and Newnham (1952) have made continuous recordings of the liquid-water content, during horizontal traverses of small cumulus clouds, which well illustrate its irregular variation within the cloud. The peak values which they measured were less than $\frac{1}{2}$ g/m^3, less than a quarter of the values corresponding to the adiabatic ascent of air from the cloud base. No reliable measurements of liquid-water concentration within large clouds have been published. Values have been inferred from the rate of accretion of cloud droplets upon riming cylinders and discs, but these are mostly averages across the whole extent of clouds, which must inevitably be much smaller than the maximum local concentrations likely to occur in the bubble centres. Moreover, Ludlam (1951) has shown theoretically, and Fraser, Rush and Baxter (1952) have confirmed experimentally, that this method is incapable of measuring high concentrations at temperatures not far below 0°C.

The observations made during the Thunderstorm Project contain an unrivalled series of measurements of updraught speeds in thunderstorms. Maximum speeds of about 10 to 25 m/sec were observed at heights of 10,000 ft to 25,000 ft, in clouds which mostly reached above 35,000 ft and occasionally reached 50,000 ft. The most frequently encountered width of updraught was about 5,000 ft, which supports our estimate of rather less than 2 km for the characteristic width of individual bubbles.

It is interesting that the radar examination of these storm clouds indicated that a particular ' cell ' giving a well-defined radar echo was a large cloud containing a number of smaller active units called ' turrets,' and which represent individual columns or bubbles. Thus it was observed that the highest echoes were built in steps, in which successive turrets extended above the top of the first-formed column of echo. The second turret usually extended about 5,000 ft above the first, which is about the additional penetration into clear air which would be expected if a bubble of about this width emerged relatively undiluted from the previous cloud tops.

The measurements so far made inside large clouds do not provide reliable information on the important question of how much dilution is suffered by the bubbles which rise through their interiors. However, the fact that the lapse rate in the clear air outside large clouds is often little different from the wet adiabatic suggests that in these circumstances there can be very little dilution. Espy, Klein and Palladino (1945) developed a fairly successful method of forecasting the level of cumulus tops in polar air outbreaks over the northern North Atlantic; this method consisted of predicting the temperature at the cloud base (from the sea-surface temperature and an assumed surface humidity), and finding the point of intersection of the wet adiabatic through the point thus defined on an aerological diagram with a curve representing the initial temperature distribution in the unmodified air mass, adjusted to allow for a mean vertical motion. The cloud tops were forecast to be 750 ft higher, and a test using aircraft cloud observations showed the prediction to be in error by 3,000 ft on only one occasion out of forty. This work is a straightforward application of the parcel theory, and its success indicates that no significant dilution of bubbles occurs inside these clouds, since Scorer and Ludlam (1953) have shown that the bubbles cannot be expected to ascend much above the equilibrium level at which their buoyancy becomes zero.

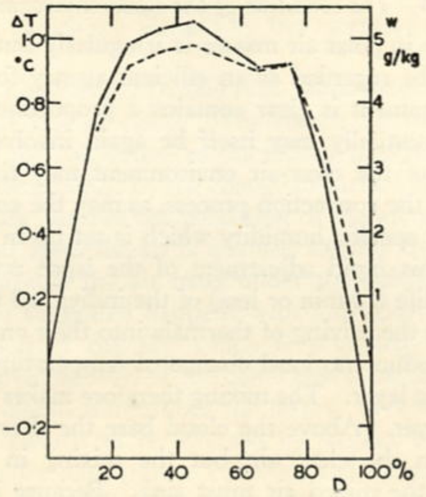

Figure 2. The average maximum temperature excess ΔT at various fractions D of the cloud depth, for 77 observations of cumulus more than 200 mb deep, made over the northern North Atlantic during Oct.-Mar. 1943-4 and Oct. 1944. The pecked line shows the liquid-water concentration w which could be supported by the buoyancy due to the excess temperature, assuming that this already at the cloud base amounted to 0·27°C.

Some support for this view is provided by an examination of the cumulus observations and simultaneous soundings made over the northern North Atlantic by British meteorological-flight aircraft during the war. When large clouds were observed (of depth greater than about 7,000 ft), their tops were almost always very close to the equilibrium level of the parcel theory, provided that it was determined by wet adiabatics calculated with respect to liquid water even at temperatures below 0°C. The cloud tops were usually well above the level indicated by Petterssen's theory, namely where the lapse rate first becomes equal to the wet adiabatic. This is illustrated in Fig. 2. It was obtained from an analysis of 77 soundings made during the months of October-March 1943-4 and October 1944, and shows the average difference between the temperature observed in the clear air, and that corresponding to adiabatic ascent from the cloud base, as a function of the cloud height. The average temperature at the cloud base was about 5°C, and the values of actual temperature difference can be regarded as differences of virtual temperature. It will be seen that the virtual temperature excess increases upwards from the cloud base to reach a maximum average value of about 1°C nearly half-way to the cloud tops, and then suddenly decreases near the tops to become − 0·27°C at the level of the tops.* On only eight of the soundings did it anywhere reach 3°C. In general the virtual temperature excess is sufficient to give a positive buoyancy to cloud air containing the maximum possible condensed-water content, except within some $\frac{1}{2}$ km to 1 km of the cloud top. This suggests that the bubbles which compose the cloud tops are protected from considerable mixing within the cloud, but suffer rapid dilution and evaporation on emerging near the summit level. It must be emphasized that this conclusion is valid only for the largest clouds of all those present, and only when they are more than about 7,000 ft deep. The observations were not sufficiently detailed to warrant a similar discussion when the clouds were smaller, but it was clear that on many such occasions their tops were considerably below the equilibrium level of the parcel theory, and this of course must also have been true for the majority of the cumulus present on the days for which the soundings were analysed.

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* This suggests that inside the cloud bases the virtual temperature was about 0·27°C higher than that observed in the clear air at their level.

7.4 *The condition of the cloud environment*

Cumulus over the sea in polar air masses is irregularly but fairly evenly distributed, and the convection may be regarded as an efficient agency for stirring and mixing the air. Air which at one moment is clear contains a proportion of more or less recently evaporated cloud, and eventually may itself be again involved in cloud formation or growth. The condition of the clear-air environment may therefore be considered an instantaneous property of the convection process, as may the condition of nearly constant potential temperature and specific humidity which is set up in the air beneath the cloud base. We may regard this rapid adjustment of the lapse rate to the convection as a consequence of the short life (20 min or less) of the individual thermals and clouds.

Below the cloud base the mixing of thermals into their environment warms this air, while vertical motions produce no local change of temperature except near the ground and the top of the adiabatic layer. The mixing therefore makes the principal contribution to the warming of this layer. Above the cloud base the thermal bubbles may become considerably warmer than the clear air, but the mixing in general chills, and after the evaporation of cloud the mixed air must sink. Because it then warms at the dry adiabatic rate it does not settle far in the layer of near-saturated-adiabatic lapse rate before reaching equilibrium with the outside air. In the cloud layer, therefore, the mixing processes produce no local heating, and the warming of this layer can be regarded as due to widespread settling motions which occur between the cloud updraughts in the manner already indicated. Superimposed upon and inseparable from these motions are the widespread vertical movements due to disturbances on a synoptic scale. These therefore exert a controlling influence upon the convection. They are most pronounced in the middle troposphere, and hence the upward movements associated with low-level convergence, perhaps caused solely by the warming due to the convection itself as previously discussed, tend to exaggerate and maintain the convection, while widespread subsidence tends to suppress it. The existence of general upward motion is illustrated by the increase in cloudiness and the small rate of warming often observed during vigorous convection. If throughout an hour the total quantity of condensed water present in the clouds is unchanged, and if 1/10 of the sky contained updraughts of 3 m/sec, a general compensating sink of 1/3 m/sec would produce a warming of the air above cloud base of several degrees Centigrade. Such a rapid warming is not observed; if it did occur the convection would quickly be diminished.

Bunker *et al.* (1949) made a number of detailed aircraft soundings amongst the trade-wind cumulus over the Caribbean. They found a layer of practically constant potential temperature and specific humidity which extended from near the sea surface to within a few hundred feet of the level of the cloud base. Above this level the lapse rate becomes less than the dry-adiabatic and the specific humidity decreases, and over several hundred feet the lapse rate may be very small or zero. These writers therefore described it as the ' stable layer,' or the ' sub-cloud layer,' and interpreted it as an indication that there were no thermal updraughts below the cloud bases. However, it was difficult to find in relatively cloudy areas, being well marked only in large clear spaces ten or twenty miles across. It therefore seems likely to be produced by settling motions outside the cloud clusters, which cause the potentially warmer and drier clear air at cloud levels to sink some distance into the adiabatic layer before becoming incorporated into it by mixing. This settling may well be less marked within the comparatively cloudy areas, and the ' stable layer ' can be regarded as a normal feature of the temperature distribution well away from concentrations of thermals or clouds, particularly when the air mass is subject to general subsidence. Under these conditions it is not peculiar to the trade-wind regions, but also may be found during convection caused by sunshine overland, when there is no doubt that the clouds are formed by the ascent of thermals from the surface layers (Ludlam 1953).

The oceanic cumulus, observed by Bunker *et al.*, were assembled into clusters separated by large clear areas almost free of cloud. The reason for this grouping is not clearly understood, but evidently the convection in the cloudy patches is sufficient to warm the whole air mass at the rate determined by the change in surface temperature and the general convergence. In the cloudy patches the condition of the air will be that appropriate to the convection; in the clear areas the air is warmed steadily by subsidence. The cloudy areas probably migrate through the air mass under the influence of the wind shear, as Scorer and Ludlam (1953) suggested happens with individual clouds.

In general the fraction of the sky which is occupied by the cloud updraughts diminishes with height above the level of the cloud bases, because individual clouds taper upwards and the smaller clouds outnumber the larger. We may then expect the same rate of transfer of heat upwards to be effected by weaker updraughts near the cloud bases, associated with smaller temperature excesses, and therefore the clear air sounding on the aerological diagram is broadly a curve concave towards the wet adiabatic through the point representing the cloud base. Above the cloud-base level, in the region of lapse rate greater than the wet adiabatic, we may expect bubble agglomeration to occur within large clouds, just as there is thermal agglomeration in the dry air close to the ground where the lapse rate exceeds the dry adiabatic. The exact nature of the temperature and humidity variation throughout the convective layer is determined by the peculiar properties of the clouds and the distribution of general vertical motion.

7.5 *The control of convection by large-scale disturbances*

The maximum height to which convection can reach, in an air mass heated at the surface, is the level at which the air, if saturated at the same temperature, would possess the wet-bulb potential temperature of the air near the surface. It is therefore dependent upon the modification of the high-level temperature distribution by widespread vertical motion, and upon the temperature and humidity at the surface. Over a particular stretch of ocean the latter parameters vary little from average seasonal values, and therefore during convection in polar outbreaks of constantly recurring character the most important factor in determining the upper limit of the convective layer, that is the level of the cumulus tops, is likely to be the widespread vertical motion associated with synoptic-scale disturbances. In this connection it is interesting that Crutcher *et al.* (1950), forecasting the height of cumulus tops on the Washington-Bermuda air route, found a striking relation between the observed height and the vorticity of the streamlines at the 700-mb level in the vicinity of the observed clouds. The correlation coefficient varied from 0·73 to 0·89 when 454 observations were grouped by months of the year. The height of the cloud tops varied from about 7,000 ft with zero vorticity to over 20,000 ft with the more intense cyclonic vorticities, which presumably were associated with upward motions. Petterssen *et al.* (1945) also found a similar relation, the vorticity of the 750-mb flow being cyclonic in 94 per cent and absent in the remaining 6 per cent of the occasions in their analysed data when cumulus over Britain reached or surpassed the 400-mb level. Forecasters are of course well aware of the close association of strong convection and the synoptic situation.

Bryson (1951a) has pointed out that over the tropical oceans air-mass and sea-temperature variations are insignificant factors in determining the development of cumulus convection, which is controlled almost entirely by the synoptic situation. He devised a scale on which to represent the degree of cloud development, and used it to investigate the patterns of cloud development in different kinds of weather disturbances (1951b).

7.6 *The diurnal variation of convection*

Bryson also showed that over the open ocean in the west Pacific there is very little diurnal variation in cumulus activity; if anything, the nocturnal clouds were rather less well developed. This stands in marked contrast with the nocturnal maximum of thunderstorm frequency which occurs in many coastal waters and enclosed seas.

Over land masses, convection is almost always due to the heating of the ground by sunshine, and there is a marked diurnal variation. Above the level of the cloud base there are often only very small changes in the temperature distribution, but the clouds which form early in the day are small even though the parcel theory suggests that cloud air could ascend to great heights. This is because the small rate of heating and the plentiful distribution of thermal sources cause the thermals to be small, well-scattered and produced only intermittently at particular sources. As the heating progresses larger thermals are produced, and in more rapid succession over favourable sources, so that bigger clouds can be built. Hills which, as described previously, are especially prolific thermal sources, are of special importance in the production of large clouds. On the other hand over valleys persistent subsidence subdues or even suppresses the cumulus growth.

The clouds usually attain their maximum development about the time of maximum surface temperature, but occasionally when there is an inversion or stable layer not far above the cloud base the cloud bubbles reach it and spread out to form a stratocumulus-cumulogenitus which shades the ground and reduces the convection. On other occasions the level of the cloud tops changes little while the level of the cloud bases rises steadily with the progressive warming of the surface layers, so that the clouds shrink and may eventually disappear.

When the surface temperature has fallen one or two degrees below its maximum the superadiabatic layer near the ground disappears; there is now no source of air potentially warmer than that in the adiabatic layer, except locally where the surface temperature is maintained on slopes facing the sun and other favourable sites. The clouds therefore decrease in size and number and usually disappear considerably before sunset. Towards sunset the stabilization of the lower layers may cause the formation of wave motions near hills, sufficient to cause a renewed condensation at about the previous cloud-base level, where a lift of only several hundred feet is sufficient to bring the air to its dew point. The clouds thus formed are in an environment whose lapse rate is steeper than the moist adiabatic and, unlike the typical wave clouds, they break up into an irregular small-scale convective pattern and may drift away from the hills as patches of stratocumulus, which is often mistakenly described as cumulogenitus.

In the late evening the normal daytime pattern of mean upward air motion over hills and settling over valleys is reversed. The nocturnal upward movement of air over valleys, and over lakes and enclosed seas surrounded by land breezes, may lead to a renewed condensation over these regions and appears to be the cause of nocturnal maxima of thunderstorm frequency. These have been shown to occur on the coasts of the Great Lakes and of Lake Victoria, for example, and Neumann (1951) has found that in the eastern Mediterranean and some other places there is a daytime maximum of thunderstorm frequency near coasts which project into the sea, and a night-time maximum near coasts which are concave towards the sea and which presumably cause a convergent land-breeze flow to develop over the coastal water. Brückner (1951) has described the regular sequence of daytime hill thunderstorms and night-time valley storms in Colombia, and Bleeker and Andre (1951) propose that the nocturnal maximum of thunderstorm occurrence over the central plains of the U.S.A. is due to the same process operating on an even larger scale.

Presumably widespread layer clouds are first formed in the lower layers and provide the heat source for the assembly of large cumulus clouds, but the details of the development of the cloud systems of these nocturnal thunderstorms have not been investigated and are not understood.

7.7 *Forecasting the development of cumulus clouds*

We see that over sea and land alike the development of cumulus clouds is powerfully controlled by large-scale flow patterns associated with a general ascent or subsidence. When the clouds are widespread the details of the process of cumulus convection, together with these large-scale movements, determine the depth of the convective layer and the distribution of temperature and humidity within it, and thereby also the distribution of buoyancy, updraught speed and condensed-water content inside the clouds. Even when the relations between the latter properties and the sounding representative of the clear-air environment have been established, it will not be profitable to attempt forecasting the one directly from the other, except perhaps in those instances over land where the convective clouds grow over isolated sources, occupy a very small fraction of the sky and do not exert much control over the properties of their surroundings. To make a successful forecast of cumulus development information will be required on the present condition of the air mass to be heated, on the rate of heating and other surface features which are likely to determine the characteristics of the cloud population (well-scattered, or locally concentrated over favourable sources), and the future large-scale vertical motion. The influence of the last feature is so strong that in the present state of knowledge consideration of the synoptic situation is more important than the detailed examination of recent soundings and temperature changes. This is recognized in forecasting practice, though not perhaps so widely in the literature. However, it has often been expressed by Douglas (e.g., 1920), and recently Byers and Rodebush (1948), in discussing the importance of sea-breeze convergence as a cause of the frequent thunderstorms in Florida, mention that they could find no clear relation between soundings and the development of thunderstorms. Means (1952) has related thunderstorm occurrence to the cross product of the pressure and temperature gradients on 850-mb charts, i.e., in effect to the baroclinity of the lower atmosphere, which he recognizes is probably more pronounced in regions where there is general vertical motion. Sutcliffe (1952) says that ' a forecaster will give a good estimate of convective activity from his prebaratic chart . . . . without even troubling his head about the probable lapse rates.' This does not of course imply that he is as successful as he would wish.

The possibility of relating the convection to the isobaric pattern suggests that numerical methods of computing the pressure changes may eventually be able to include the heating due to convection in the equations without any mathematical formulation of the process of convection.

8. CONCLUSION

8.1 *Requirements of improved theories of cumulus convection*

New theories of cumulus convection are required to account for the properties of individual clouds and for the general depth and structure of convective layers. In the first place some model is needed of the air motion which occurs when a bubble of cloud air ascends through a dry environment. The manner and the effects of mixing determine the height through which it rises before evaporation, and the distribution within it of updraught speed and concentration of condensed water. Next, the character of cumulus populations must be examined; the distribution and strength of the thermal sources, together with the large-scale weather features and processes attending the growth and decay of individual clouds, determine the depth and the degree of the modification of the air mass by the convection, and also the size and vigour of the cumulus clouds.

The difficulty of the problem is as great as that in any other aspect of meteorology, but because the convective phenomena are so important and spectacular there is no scarcity of workers to tackle it, and we may expect steady progress.

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