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Convection in the atmosphere

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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