The New Ideas in Meteorology.¹

By Dr. G. C. SIMPSON, F.R.S.

THE first quarter of the twentieth century will always be remarkable for the great advances made in science. In our own particular branch the advance has probably been the most startling and has appealed very strongly to the popular imagination. In mathematics we have had a little-known and even less-understood branch of pure mathematics applied to physical problems with results which have revolutionised our whole conception of the universe in which we live. In astronomy we have had described to us an evolution of the heavenly bodies as real and as dominating as the evolution which the previous century revealed in the animal kingdom. In physics the progress made has been most remarkable. At the beginning of the century, it is true, we had been introduced to the electron, to Röntgen rays, and to radioactivity; Planck was also writing on the laws of radiation; but no one realised the powerful tools which these phenomena were going to put into the hands of physicists. These tools have, however, been used, and not least by our own countrymen, to dig deep into Nature's secrets, even into the atom itself, so that now we are able to visualise the component parts of an atom, which itself is a structure far removed from our powers of perception.

Meteorology, although a child of applied mathematics and physics, has scarcely been touched by the epoch-making discoveries in the house of its parents. The quantum has found no place in our theories of the mechanism of the atmosphere; a knowledge of the structure of the atom has not helped us to understand the physics of the air as we deal with it in meteorology; the relationship between mass and charge, the invariability of the velocity of light, four-dimensional space and all the other new conceptions which have been responsible for the advance of physics, have been of no help to meteorologists in their especial branch of science.

The whole attention of physicists has been so dominated by these new ideas, and the vistas of unexplored country which they have opened out are so vast, that it is no wonder that physicists have had no interest in a domain in which their new tools could not be employed. The consequence has been that meteorology has had little help from physicists and mathematicians as such, and has had to depend, at least in Britain, on the relatively small band of meteorologists in Government employ. Let me say, however, that we are grateful for the help which we have received from physicists, especially from those who were brought into contact with meteorology during the War. In spite of the fact that meteorology has not been able to make use of the recent discoveries in pure physics, there has been in the last twenty-five years as fundamental a revolution in our ideas of the atmosphere as has taken place in our ideas of electricity and matter. Unless I am very much mistaken, however, these fundamental changes in our conception of the atmosphere, both as a whole and in its parts, are

little known outside the small band of professional meteorologists. I therefore welcome this opportunity of bringing them before the members of Section A of the British Association.

THE THERMAL STRATIFICATION OF THE ATMOSPHERE.

The fact that the temperature of the air decreases as we ascend in the atmosphere has been known from time immemorial, but our real knowledge of the temperature of the free air dates only from 1898, when Teisserenc de Bort introduced his *ballons-sondes*, which carried self-recording instruments to heights in the atmosphere up to that time never attained and from which no information was then available.

The initial success of Teisserenc de Bort in his epoch-making discovery of the stratosphere attracted great attention to his investigations. His methods were introduced into other countries, and an intense investigation of the upper atmosphere, with an International Commission to guide and encourage it, was inaugurated. In Britain, Mr. W. H. Dines did Trojan service in the cause, and his observations and deductions are outstanding in the mass of data accumulated in many parts of the world. Naturally the conditions over Europe and North America were investigated in the greatest detail, but every opportunity has been taken by meteorologists to obtain upper-air data from all parts of the world. In addition to the regular observations undertaken in most countries having an organised meteorological service, expeditions have gone out specially to investigate the upper atmosphere over the oceans and over tropical Africa, and nearly all recent polar expeditions have included this investigation amongst their scientific activities.

There are, of course, large tracts of the earth's surface above which no observations have yet been made, but some, if only a few, observations have been made in all meteorologically important areas, including both polar regions. It is on the results of these observations that we base our conception of the thermal structure of the atmosphere, and meteorologists have attempted from them to generalise the conditions in all parts of the world. The most important generalisation of this kind has been made by Sir Napier Shaw and published in the form of diagrams in his book, "The Air and its Ways."

Probably every one here is familiar with the main results of these investigations. The atmosphere, which itself is an extremely thin film of air, is composed of two shells surrounding the earth. In the lower of these shells, called the troposphere, the temperature decreases as one rises in the atmosphere, and the air is warmer over the equator than over the poles at corresponding heights. In the upper shell, called the stratosphere, the temperature conditions are entirely different. There is little or no change in temperature with height, and the horizontal change of temperature is reversed, the temperature at the same height in the stratosphere decreasing as one passes from the poles to the equator. At the earth's surface the mean

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annual temperature near the equator is $27^{\circ}\text{C}.$, and at the poles $-23^{\circ}\text{C}.$; *i.e.* the equator is $50^{\circ}\text{C}.$ warmer than the poles. At twenty kilometres above the surface the temperature over the equator is $-80^{\circ}\text{C}.$, and over the poles $-30^{\circ}\text{C}.$; that is, the temperature difference between the equator and the poles is the same in amount at the surface and at a height of twenty kilometres, but in the former case it is the equator which is the warmer, while in the latter it is the polar regions—a truly remarkable reversal.

The surface of separation between the two shells, called by Sir Napier Shaw the "tropopause," is extremely sharp. There is no region of transition. The stratosphere sits on the troposphere like a layer of oil on a layer of water. The boundary is, however, not horizontal, and therefore not exactly concentric with the earth's surface, being higher at the equator than at the pole. In other words, the lower atmospheric shell, the troposphere, is thicker at the equator than at the poles. At the equator it is nearly twenty kilometres thick, while at the poles it thins down to a layer less than six kilometres thick in the summer and less than four in the winter.

I have already said that in the troposphere the temperature decreases as one ascends. The magnitude of this decrease varies from place to place and from time to time, but one remarkable result has come out of the investigation, and that is that the average decrease is practically the same in all parts of the world. Near the ground the conditions are complicated; here the rate of decrease is largely affected by such factors as the kind of surface, whether land or water, the time of day and the time of year. If we omit for this reason the two lower kilometres of the atmosphere, we are able to state that the rate of decrease of temperature with height, to which I shall refer as the "lapse rate," is the same in all parts of the world, from the equator to the poles. The lapse rate is not the same at all heights, but increases regularly as one ascends. Between two and four kilometres above sea-level the rate of decrease is $5.6^{\circ}\text{C}.$ for each kilometre of ascent; the rate is greater at greater heights, until towards the top of the troposphere, say between six and eight kilometres, the rate is $7.1^{\circ}\text{C}.$ per kilometre.

The importance of these results lies in the bearing they have on the possibility of vertical motion in the atmosphere. Whether air will rise or fall as the result of differences of temperature depends not only on an initial difference of temperature but also on the lapse rate in the surrounding atmosphere. When dry air rises its temperature falls on account of adiabatic expansion $10^{\circ}\text{C}.$ for each kilometre of ascent. From the observed values of the lapse rate given above, it will be seen that if a mass of air is as much as $10^{\circ}\text{C}.$ warmer than its surroundings it cannot rise much more than two kilometres before it has no buoyancy left. The question of ascending and descending air is, however, very complicated on account of the condensation of the water vapour carried with it. The vertical motion of the atmosphere cannot be determined simply from consideration of the lapse rate of temperature in the atmosphere. We have also to take into account the pressure and vapour content of the moving air. This can best be done by considerations of entropy.

Sir Napier Shaw has prepared diagrams showing the entropy throughout the normal atmosphere. These show surfaces of constant entropy which are nearly horizontal, but they slope upwards from the equator to the poles, especially in the lower layers. If these surfaces could be made visible, we should see a series of layers lying one above the other like the strata in a geological specimen of stratified rock.

In all movements of the air in which heat is neither added nor extracted—for example, by condensation or radiation—it must travel along an isentropic surface. Even if condensation takes place, the amount of heat added is usually so small that the air can only move to a neighbouring isentropic surface slightly higher in the atmosphere. These isentropic surfaces act like physical restraints to the air, tending to prevent its moving in any but an almost horizontal direction. The effect is almost exactly as though the atmosphere were definitely stratified in nearly horizontal planes, so that all motion of the air must take place along the strata in which it started.

This is what I mean by the thermal stratification of the atmosphere, and it is a new idea in meteorology, for it rules out ascending and descending currents as a direct consequence of the normal temperature distribution in the atmosphere. That ascending currents do occur and play a large part in atmospheric processes is, however, a matter of both observation and inference. We can actually see them taking place whenever we observe well-developed cumulus clouds, and we infer them from the large amounts of precipitation which we measure, for appreciable precipitation can only be accounted for on the assumption that air is rising in the atmosphere and cooling by adiabatic expansion. These ascending currents are possible in the stratified atmosphere only if the air taking part in them receives sufficient heat on its ascent to raise its entropy at least to that of the surrounding atmosphere at each level. Heat is supplied by condensation of water vapour, but normally air does not hold sufficient water vapour, even when saturated, to supply the requisite heat, and so cannot pierce the normal stratification. It sometimes happens, however, that the stratification is less pronounced than at other times. The greater the lapse rate the less the stratification, and by increasing the lapse rate sufficiently the stratification can be reduced to such an extent that there is sufficient water vapour to supply the heat required. When this occurs the atmosphere becomes unstable to saturated air and ascending currents take place, generally with considerable violence.

Such conditions give rise to thunder-storms, which occur, as is well known, only when the lapse rate has been abnormally increased, generally by the heating of the surface layers faster than the layers higher in the atmosphere. Also in equatorial regions over the ocean, where the air is very hot and also very humid, there may be sufficient water vapour in the air for it to rise through the normal stratification. This is the origin of the squalls and heavy rain in the Doldrums. From this it will be seen that the ascent of air through its environment is not a normal phenomenon, but does occasionally occur in special circumstances.

The descent of air is an entirely different matter, for there is no process which extracts heat from a

descending current equivalent to the process of condensation which supplies heat to an ascending current. Yet air cannot descend through the stratification without the necessary heat being extracted. On the other hand, we do know that air descends, for the air which goes up in the ascending currents, or rather an equivalent amount, must come down somewhere. The solution of the problem is that air practically never descends through its environment, but comes down by the gradual subsidence of a whole column. This is generally brought about by the air at the bottom of the column spreading under the surrounding air and so lowering the air above in a way to be described in greater detail later.

If now we consider the undisturbed atmosphere in different parts of the world, we find that each has its own stratification, which is mainly determined by the local radiation. At the equator the stratification is not so close as at the poles, and equivalent strata are higher in the atmosphere the farther we move from the equator. If a large mass of air is transported as a whole without gain or loss of heat, no change in entropy occurs, and therefore it retains its original stratification. It is therefore clear that if masses of polar and tropical air are brought together the strata will not fit. The process is something like removing two geological specimens from different parts of a stratified rock and then placing them side by side. We can recognise the surface where the two masses meet by the discontinuity in the strata; in geology such a surface of discontinuity is called a fault. We shall consider later the consequence of bringing together masses of air of different origin in this way, and it will be shown that they interact like separate fluids, but throughout the resulting motion they retain their stratification, although this stratification becomes modified and distorted.

This idea of the stratification of the atmosphere which has caused us to recognise that ascending and descending currents are relatively rare occurrences raises new problems as to how the solar energy is converted into the kinetic energy of winds. This leads me to the second subject of this address.

THE MECHANISM OF THE ATMOSPHERIC HEAT ENGINE.

Brunt has calculated from considerations of wind and atmospheric friction that 25×10^{11} kilowatts of energy are required to maintain the motion of the atmosphere. It is generally agreed that this energy is derived from the solar radiation which falls on the earth, the atmosphere itself acting as a gigantic heat engine to convert the solar energy into the kinetic energy of the winds. How the atmospheric heat engine works is the problem which we are now to discuss.

Until quite recently this problem seemed to present no difficulty. All atmospheric motion was referred in one form or another to the ascent of warm air through cold air and the descent of cold air through warm air. The so-called general circulation of the atmosphere was considered to be the direct consequence of the ascent of warm air at the equator and the descent of cold air at the poles, there being a permanent circulation from the equator to the poles in the upper atmosphere, with a return flow in the surface or middle

layers. Similarly cyclones were considered to form in regions where the air is warmer than the surrounding air, with a consequent upward motion of the warm air through its colder environment. The anticyclone, on the other hand, was considered to be a region of cold descending air. Thus cyclone and anticyclone were regions of ascent of warm and descent of cold air respectively.

I have already shown, however, that the thermal stratification of the atmosphere, except in the Doldrums and occasionally in other regions, is prohibitive of such ascending and descending currents. Further, observations have shown that there is no direct flow of air from the equator to the poles in the upper atmosphere, and measurements of temperature in cyclones and anticyclones have shown that the former are not warm and the latter are not cold.

Although the old ideas were wrong in detail, they were, of course, right in principle, for the potential energy inherent in masses of air at different temperatures must be the origin of the kinetic energy of the winds, the difference in temperature between the equator and the poles being responsible for the general circulation of the atmosphere, and the difference in temperature between neighbouring masses of air for the energy of cyclones and anticyclones. The only question is, how does the transfer from potential to kinetic energy take place?

The solution of the problem was given by Margules in a series of papers, commencing in 1903, in which he investigated the energy developed in storms. Margules' work leads to an entirely new idea as to the method by which solar energy is converted into the kinetic energy of atmospheric motion. Instead of warm air rising vertically like the warm gases in a chimney, drawing air in at the bottom and delivering it at the top, we see two bodies of air, one warm and the other cold, brought side by side, then the cold mass slowly subsiding and pushing its way as a wedge of cold air under the warm air, which is partly raised and partly drawn in above to replace the cold subsiding air. In the process the centre of gravity of the whole moving mass is gradually lowered, so providing the energy for the motion which we recognise as winds.

The essential difference between the new and the old idea is that the two masses of air, in which the difference of temperature is the cause of the motion, never mix. We start with the two bodies of air side by side, with a surface of sharp discontinuity between them. In each body there is a different stratification of isentropic surfaces. In the warm body of air the corresponding isentropic layers are all lower than in the cold body of air. As the cold mass subsides its isentropic layers are lowered, while as the warm air is raised its isentropic layers are raised with it; but the surface of discontinuity between them, which I have previously likened to a geological fault, is a sliding surface, and no air crosses it. The sliding motion does not cease until either the corresponding isentropic layers on the two sides have joined up across the surface, which then ceases to be a surface of discontinuity, or until all the warm air has been raised above the cold air and the surface of discontinuity becomes a horizontal plane. The two masses are then in equilibrium without any mixing having taken place.

SURFACES OF DISCONTINUITY.

The process which I have just described would take place very rapidly on a stationary earth, and in a short time the surface of discontinuity would disappear in the manner described or appear as a horizontal surface with all the cold air underneath and all the warm air above. But in the atmosphere we find inclined surfaces of discontinuity persisting for days together, and others which are apparently permanent. This arises from the effect of the rotation of the earth, which we have so far neglected, but which introduces new forces when air is in motion.

A mathematical investigation of the conditions governing the air motion at surfaces of discontinuity has shown that, on a rotating earth, the tendency of cold air to pass under warm air can be completely counterbalanced by forces due to the earth's rotation if the air on the two sides of the surface has suitable relative velocities.

We owe the mathematical investigation of this problem chiefly to Helmholtz, Margules, V. Bjerknes, and Exner.

Two bodies of air at different temperatures will remain in equilibrium side by side if suitable motion parallel to the boundary is given to the air on each side. The angle which the surface of discontinuity makes with the horizontal depends on three factors, namely, the latitude and the difference in temperature and relative motion of the warm and cold currents. Given steady motion, these three factors adjust themselves in a perfectly definite way, with the cold air lying as a rule in the acute angle which the boundary makes with the horizon.

V. Bjerknes considers that there are three great permanent surfaces of discontinuity of this kind in the atmosphere, and that the slope of the surface in each is in accordance with the discontinuities of the wind and density observed on the two sides. Taking these in turn, the first is the great surface of discontinuity between the troposphere and the stratosphere. The second surface of discontinuity is between the trade winds and the anti-trade winds above them. Bjerknes' third surface of discontinuity, which has received the name of the "polar front," is a very important one in modern meteorological theory. On the whole there is very little air motion in polar regions, and the cap of air over each pole is losing heat by radiation and so tending to subside and flow away from the pole. As the air from the polar cap flows radially outwards it is deflected to the west on account of the earth's rotation. On the other hand, in middle latitudes, from near latitude 30° to the polar circle, the air is moving in an almost unbroken stream from west to east. Relative to the air in the polar cap this air is very warm. We therefore have a cold cap of westerly-moving air embedded in a warmer mass of air moving towards the east, and between the two there must be a pronounced surface of discontinuity. In such conditions the surface should slope upwards toward the pole. V. Bjerknes considers that there are such surfaces of discontinuity associated with each pole and that they are very stable. These "polar fronts" play a large part, as we shall see later, in Bjerknes' theory of the formation of cyclones.

But these are not the only surfaces of discontinuity

which play a very real part in the physics of the atmosphere. While the three surfaces just described are of a more or less permanent nature, we now recognise a constant succession of temporary surfaces of discontinuity which form and pass away in our own latitudes. Their presence is revealed in many ways. On the synoptic charts lines can be drawn which divide regions in which the conditions at the surface as regards temperature, humidity, and wind velocities are entirely different. These lines are simply the intersection at the earth's surface of the surface of discontinuity between two bodies of air.

THE ORIGIN AND STRUCTURE OF CYCLONES.

The old idea of a cyclone was tersely expressed by Sir Oliver Lodge, in a letter to the *Times* last year, as follows: "A cylindrical vortex with its axis nearly vertical, rolling along at a rate conjecturally dependent partly on the tilt, and with an axial uprush of air to fill up a central depression, which depression, nevertheless, was maintained and might be intensified by the whirl, the energy being derived from the condensation of vapour." If this were the true mechanism of a cyclone we should expect to find considerable symmetry around the axis. The air would move in a continuous stream circulating around the centre but always approaching it; in other words, the stream lines would be continuous spirals. There would also be little difference of temperature in the different parts of the cyclone, for the same air current would pass successively through all parts. In reality the conditions are entirely different. When stream lines are drawn by the aid of the wind arrows on synoptic charts it is impossible to connect them so that they circulate all round the depression; we find, on the contrary, that they are discontinuous, the stream lines in certain parts meeting the stream lines in other parts almost at right angles. Also we find large discontinuities in the temperature, each set of stream lines having its own temperature. Further, we find that the areas of rainfall are not confined to the central regions, but are broad bands radiating from the centre like spokes in a wheel, showing that the ascending air is not taking place mainly in the central region.

As the result of recent work we now recognise a structure in a cyclone which was unknown a few years ago. We owe this new knowledge largely to the work of J. Bjerknes and his assistants in the Bergen Geophysical Institute.

We are being forced more and more to recognise in cyclonic depressions the meeting-place of polar and equatorial air. Each body of air is stable to vertical currents within itself, but where the two masses meet, readjustment is necessary; the surfaces of discontinuity tend to set themselves at the angle necessary for stability under the existing condition of velocity and temperature. This involves the bodily raising of the warm air over the cold air and a general sinking and spreading out of the cold air. The energy for the process is derived from the conversion of potential energy into kinetic energy, as the centre of gravity of the air as a whole is slowly lowered during the readjustment of the air masses. The energy derived from the condensation of water vapour is a very insignificant part of the energy developed in a cyclonic depression.

It must be admitted that we are still far from a complete understanding of the mechanism of cyclonic depression; on the other hand, we now know some features which are common to all depressions, and we have a much clearer idea of the source of the energy and the conditions necessary to their production. We have to imagine that in polar and tropical regions the air is relatively stagnant, and so has an opportunity to reach the state of thermal equilibrium appropriate to those regions. As already stated, the atmosphere is only a thin film, and we picture large areas or slabs of this film breaking away from their proper locality and moving into middle latitudes. Apparently the detached films move as a whole, at least to a considerable distance within the stratosphere. When two such portions of the atmospheric film come into juxtaposition they are not in equilibrium relative to one another, and readjustment must take place. The surface of contact remains more or less intact, but the cold air tends to sink and undercut the warm air, while the warm air slides up the surface of discontinuity. The whole motion takes place on the revolving surface of the earth, and the forces called into play by this revolution result in the air movement taking place in what appears to be a great vortex. The energy of the winds is derived mainly from the readjustment of the centre of gravity of the air mass considered as a whole, although the latent heat of condensation provides some additional energy by supplying heat to the warmer air as it ascends the slope of the surface of discontinuity. It will be admitted, I think, that this is a radically new idea regarding the mechanism of a cyclone.

All that I have said so far refers to the cyclonic depressions of middle latitudes. As to whether the mechanism of tropical cyclones is the same or whether we have here something more of the nature of the process described by Sir Oliver Lodge, meteorologists are not yet agreed. We need more observations, especially of the conditions in the upper air over tropical cyclones, before this question can be decided. At present we must leave it an open question.

These new ideas have had a far-reaching effect on the practical applications of meteorology, especially in the domain of weather forecasting. The old method of weather forecasting was mainly empirical and based on the work of Abercrombie. Abercrombie had sketched the distribution of weather about centres of high and low pressures, and forecasting was based on the determination of the movement of these pressure distributions when they appeared on the weather chart, the assumption being made that as the pressure system passed over a place the normal sequence of weather would be experienced.

Now the forecaster has much more knowledge of what I may call the anatomy of a depression. The pressure distribution is of course still the main factor, but the forecaster searches his chart for indications of the surfaces of discontinuity, and examines the characteristics of the air masses to see whether they are of polar or equatorial origin. In this way he is able to determine the structure of the cyclone and whether it is developing or dying. Having determined where the surfaces of discontinuity are situated, he is able to say where rain may be expected, and he knows what weather changes will accompany the passage of each surface of discontinuity as it moves over the surface of the land. He is aided in this by observations taken in the upper atmosphere by means of pilot balloons and aeroplanes fitted out with meteorological instruments.

This has all resulted in greater confidence in the forecasts made, a confidence which is frequently justified by remarkably accurate forecasts. Unfortunately, the processes which take place in the atmosphere are extremely complicated, and perfect forecasts are still far from being attained. The progress made, however, is very encouraging, and, what is still more important, the paths along which further investigation must be made are clearly defined. Many more observations of the upper air are necessary, many more theoretical investigations have to be made in the quiet of the study, and there is room for many more experiments in the laboratory.

Dispersal of Butterflies and other Insects.

By E. P. FELT, State Entomologist of New York.

A 2000-mile air trip appears almost impossible for an ordinary butterfly. It is still something of a feat for an airplane. Many insects are perfectly at home in the air, fly freely here and there, and are usually believed to flit from flower to flower or from one near-by locality to another. Rarely do we think of their travelling considerable distances, and under ordinary conditions it is very difficult, if not well-nigh impossible, to establish the fact that long trips may be made by individual insects. There is a romance about these journeys as well as a practical aspect. The facts are not difficult to understand, and it should be comparatively easy for readers to arrive at satisfactory conclusions.

The "Monarch" butterfly (*Danaida plexippus* L.) is one of the commonest and most noteworthy insect travellers. Its large size and tawny colour with black and white markings make it comparatively easy to

recognise even at some distance. This is the very common "milk-weed" butterfly of the northern United States and southern Canada, the insect which occasionally attracts notice because of the immense swarms which appear in early autumn, apparently southward bound. The butterfly, although so common in the north temperate latitudes, is unable to survive our winters north of the sub-tropical portions of the Southern States. Consequently, the annual reappearance of this insect proves a considerable northward movement each year, though it does not establish the fact that the entire journey from Florida nearly to the Arctic Circle is necessarily accomplished by individuals. It may be the successive efforts of several generations working northward with the advance of warm weather.

A similar northward flight is known for the cosmopolitan "Painted Lady" (*Pyraus cardui* L.) in