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THE CIRCULATION OF THE ATMOSPHERE*

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In a high school classroom where I sat some years ago our physics teacher once put before us the proposition that the sun is the source of all our energy. Naturally we tried to upset his claim, and I finally asked him about the ocean tides. At this point he invoked the hypothesis, which was reasonably well accepted in that day, that the planets and their satellites had at one time been a part of the sun. If the sun was the source of the moon itself, it was certainly the source of the energy in the moon.

The thesis which our teacher supported to our partial satisfaction a generation ago would be much harder to defend today. For one thing, alternative hypotheses which attribute the origin of the planets to accretion rather than fragmentation have become more widely accepted. Closer to home, such devices as nuclear reactors which were then unknown are now commonplace. Yet, despite all these new developments, there remain many scientific fields where the sun may still be treated as the source of nearly all the relevant energy, and these fields continue to possess many unsolved problems which are as challenging as those encountered in some of the younger sciences. Among these fields is the study of the circulation of the earth's atmosphere.

If a fluid is subjected to non-uniform heating, a circulation will ordinarily develop. One of the problems of greatest concern to the fluid dynamicist is that of deducing from the basic law of physics the circulation which will take place in a particular fluid system when it is heated in a particular fashion. Even for some of the simplest systems—for example, a tank of water insulated on the bottom and sides and cooled at the top—the problem is but partially solved.

The atmosphere itself is a special fluid, and it is heated more strongly by the sun in equatorial and tropical latitudes than in temperate and especially polar latitudes. It must therefore possess a circulation. One of the dreams of the theoretical meteorologist has been the deduction of this circulation from basic principles, given such quantities as the mass, radius, and angular velocity of the earth, the total mass and composition of the atmosphere, and the intensity and spectral distribution of the radiation from the sun.

Actually there is some question as to whether the meteorologist can really deduce the circulation. He could undoubtedly do so if he could determine the general solution of the mathematical equations which represent the physical laws. But the exact equations are too complicated

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to be handled by any known method, and some simplifying approximations are essential. The meteorologist is already familiar with the general features of the circulation, and this knowledge will in all probability influence him in choosing among the many available approximations. For example, in many theoretical studies the complete three-dimensional distribution of the atmospheric variables—pressure, temperature, wind, moisture—is represented by the two-dimensional distributions of these variables at a few chosen levels, the values occurring between these levels being obtained by interpolation. But the number and spacing of the levels is generally based upon previous knowledge of the true atmospheric structure. In view of such circumstances, many meteorologists regard their task as that of explaining or accounting for the circulation as it is observed, rather than deducing it from basic considerations.

Before we consider how one might account for the observed circulation, let us attempt to put ourselves on a more nearly equal footing with the theoretical meteorologist by looking at some of its principal features. One of the first things to be noticed is that the total circulation is composed of identifiable circulation systems of widely differing horizontal scales. We shall first examine some of the smaller-scale systems, and then progress toward the larger ones.

Perhaps the smallest-scale system to be dignified by a special name is the dust devil. These whirling columns of dust-laden air typically reach heights of a few hundred feet, but over hot deserts they sometimes extend half a mile upward. The dust serves only to make them visible; vortices of this size often form where no dust is available, and presumably many such vortices are invisible for each one which can be seen. If a person should be struck by one, he would probably experience nothing more than a sudden gust of wind. In fact, when an unexpected gust is encountered, it is frequently a portion of a dustless dust devil. The opposing motion a few yards away may remain undetected.

Despite their general inconsequential effect upon human activity, these small systems are so numerous that collectively they comprise a significant element in the total circulation of the atmosphere. Their most obvious motion is rotary, but they also contain powerful upward currents. The dust which they raise will fall back to the ground when the circulation wanes, but in the meantime they are an effective mechanism for conveying heat from the ground to higher levels.

Occurring in many sizes, but ordinarily larger than dust devils, are cumulus clouds. Within and directly underneath the clouds the currents are mainly upward, and the compensating downward currents occur largely in and directly below the drier spaces between the clouds. Particularly in tropical latitudes, cumulus cloud circulations are one of the principal mechanisms for conveying water from the earth's surface up to higher levels in the atmosphere.

The most fully developed cumiliform clouds, the cumulonimbus, generally contain showers, and often thunderstorms. In extreme cases they are ten miles deep. In that event hail is likely, and tornado funnels may reach from the main cloud mass down to the ground.

The tornado bears a superficial resemblance to the dust devil, but the energy for maintaining it appears to come from the cloud above rather

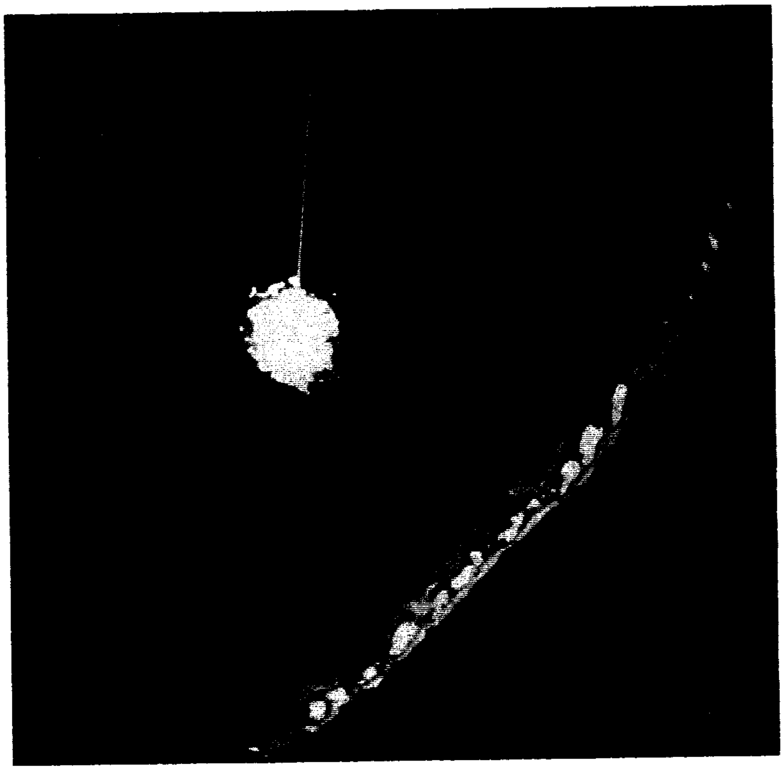

Fig. 1. A line of thunderstorms at 1930 C.S.T., May 10, 1964, as seen by the WSR-57 radar of the National Severe Storms Laboratory, U. S. Weather Bureau at Norman, Oklahoma. Photo by Charles Clark, reproduced through courtesy of the *Monthly Weather Review*.

than the ground below. It is the most violent of storms, and has received much study because of its devastating effect upon human life and property. Nevertheless, tornadoes are not a very important element in the total circulation simply because there are so few of them; if a gram of air could be picked at random from the atmosphere, the probability that it would be taken from a tornado is about one in 10^{12}.

Individual cumulus clouds are seldom randomly distributed, but tend to be organized into systems of larger scale. Figure 1 is a photograph of a radar scope, showing a long line of thunderstorms extending across eastern Oklahoma. The display is arranged in the form of a map, the location of the radar being represented by the center of the large bright spot. The line extending northward from this spot is a reference line. The storms appear to the southeast.

Ordinary clouds, whose droplets are typically a hundredth of a millimeter or so in diameter, are transparent to radar rays. Only those clouds

FIG. 2. Hurricane Betsy at 0427 E.S.T., September 8, 1965, as seen by the WSR-57 radar of the United States Weather Bureau at Miami, Florida. U. S. Weather Bureau photo, reproduced through courtesy of the American Meteorological Society.

containing raindrops (or snowflakes, or hailstones), whose diameters often exceed a millimeter, show up on the scope. This particular scope is designed so that different intensities of the reflected radar signal, resulting from different intensities of rain, show up as different shadings. The brightest spots within the line indicate the heaviest rain—in this case, thunderstorms. About twenty of these storms are organized into a line about two hundred miles long.

Lines of thunderstorms or heavy rain frequently form portions of still larger systems. Figure 2 is another radar photograph, which shows a tropical hurricane as it strikes southern Florida. The bright areas are again rain, but this radar does not differentiate between intensities. The dry central eye is plainly visible. Surrounding it is a very wet eye wall composed of towering cumulonimbus clouds, and a complex of spiral rain bands whose individual structures are somewhat like that of the line shown in Figure 1.

Photographing complete storms in visible light has recently been made possible by the satellite. Figure 3 shows a storm over the north Atlantic. The area covered by the photograph is nearly a thousand miles square. The storm, which is not of tropical origin, looks very much like the tropical storm of Figure 2. It should be noted, however, that in Figure 3 we are seeing clouds rather than rain. We may assume that rain is falling from some of the heavier clouds, but altogether the storm contains far less water than its tropical counterpart.

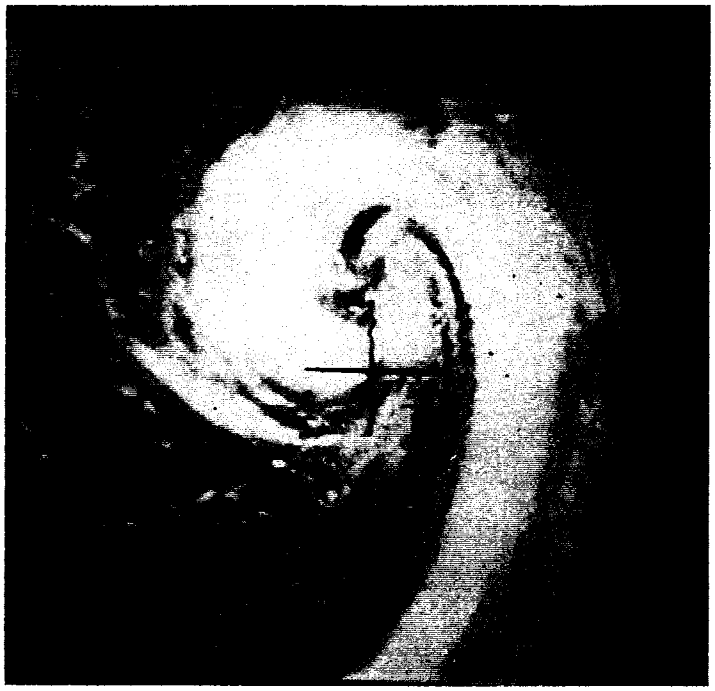

Fig. 3. A north Atlantic storm, centered at 48°N, 22°W, at 1402 G.M.T., June 11, 1964, as seen by the TIROS VII weather satellite. NASA photo, reprinted through courtesy of Aracon Geophysics Co.

To display a larger system in a single picture we may combine information obtained from different geographical locations. Some interesting results have been obtained by piecing together successive photographs from a single satellite, but most of our composite descriptions of the atmosphere are in the form of weather maps.

Figure 4 is a northern hemisphere map for a particular late winter day. The lines are isobars—lines of constant pressure, after the pressure has been reduced to sea level by a standard procedure. The relation between the pressure field and the field of motion is given to a first approximation by the geostrophic wind law. This law, which is often lesson number one to the meteorology student, states that the air moves parallel to the isobars, traveling clockwise about a high pressure area and counterclockwise about a low pressure area in the northern hemisphere, and in the opposite sense in the southern hemisphere. The direction of the geostrophic wind at sea level is indicated in Figure 4 by arrows attached to the isobars.

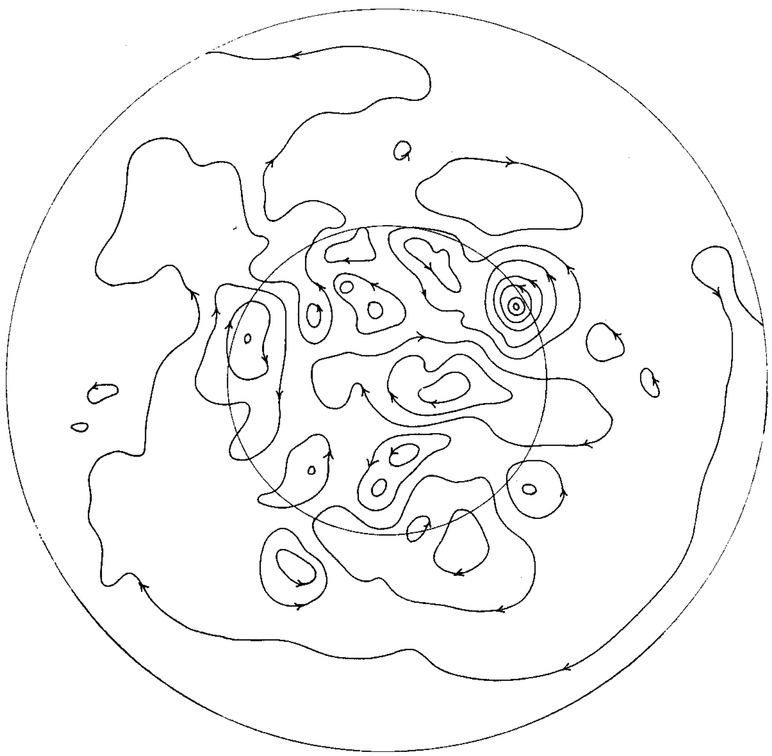

FIG. 4. Northern hemisphere weather maps at sea level, 1230 G.M.T., March 15, 1952. Outer circle is equator, and inner circle is 45th parallel. Heavy lines are isobars, and arrows show direction of geostrophic wind. Isobar positions based upon U. S. Weather Bureau analysis.

Those who have had experience with nonrotating fluids may be more familiar with motion at right angles to the isobars, toward lower pressure. Such motion will occur, for example, when the pressure force, which is directed toward lower pressure, is balanced by the force of friction, which opposes the motion. Throughout most of the atmosphere, however, friction is a minor force, and the pressure force is ordinarily balanced by the Coriolis force—the deflecting force resulting from the earth's rotation—which acts at right angles to the motion. Near the ground, friction assumes a more important role, and the wind tends to have a small component toward lower pressure superposed upon the geostrophic component. A mathematical demonstration that the forces must be nearly in balance would be extremely involved; it is simply a matter of observation that the forces do tend to balance for the most part.

Referring to Figure 4 we observe that in lower latitudes a belt of easterly winds nearly encircles the globe. These easterlies are the familiar

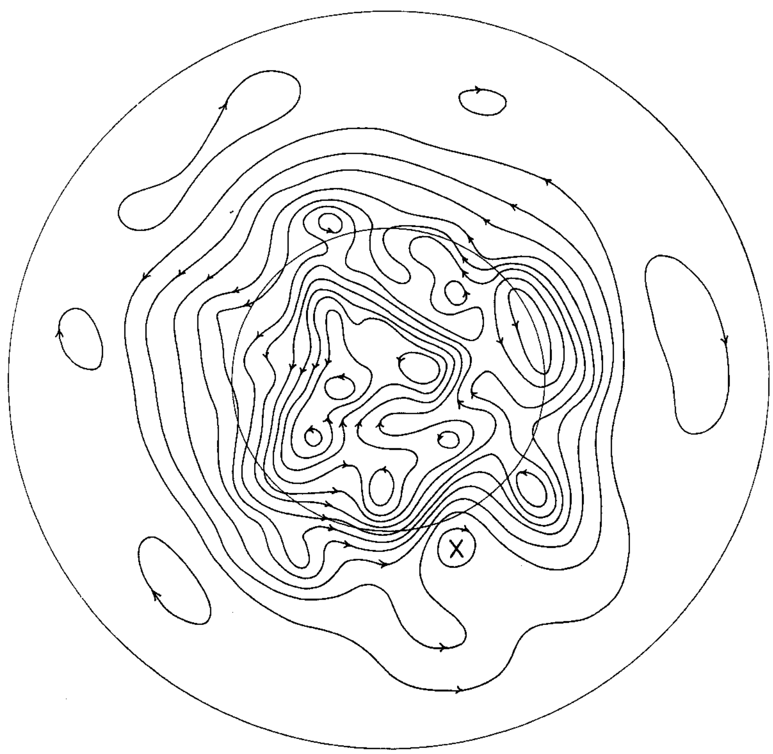

Fig. 5. Northern hemisphere weather map at 30,000 feet elevation, 1000 G.M.T., March 15, 1952. Lines have same meanings as in Figure 4. Isobar positions based upon U. S. Weather Bureau analysis.

trade winds—the steadiest of the global currents. In connection with the trades we often hear of the prevailing westerlies in middle latitudes, but in Figure 4 we see no globe-encircling belt of westerlies. If we measure the wind at a sufficient number of points in middle latitudes, and then average these measurements, we shall find a resultant wind from the west, so that the prevailing westerlies are indeed present, but only in a statistical sense. They are not present at all locations at one time, nor are they present at all times at one location. The more obvious feature in middle latitudes is the great number of anticyclones and cyclones—the centers of high and low pressure with their accompanying clockwise and counterclockwise vortices. We have seen examples of cyclones in the radar and satellite photographs.

Figure 5 is similar to Figure 4 except that it presents the conditions at an elevation of about 30,000 ft. The low-latitude easterlies are less prominent than at sea level, but the middle-latitude westerlies are much more pronounced, and form a belt which encircles the globe. Cyclones and anticyclones are still present, but to some extent they have been replaced by troughs and ridges—lines along which the pressure is lower or higher than at adjacent longitudes. The strongest winds, indicated in Figure 5 by the most closely packed isobars, form a relatively narrow continuous current which nearly encircles the polar regions; this is the now familiar jet stream. Winds as high as 200 miles per hour are not uncommon there.

The maps in Figures 4 and 5 present conditions on a single day, but the flow which they illustrate is for the most part typical of the general behavior of the atmosphere. Important features which are not present or not clearly revealed are tropical hurricanes, which are confined mainly to the summer or autumn hemisphere, and the intertropical convergence zone, a rather narrow region extending virtually around the globe where currents from the northern and southern hemispheres converge and rise, and in doing so bring about rather heavy cumulus convection, with frequent thunderstorms.

The motions of global scale—the trade winds and the prevailing westerlies at low levels, the upper-level westerlies which culminate in the jet stream, and the intertropical convergence zone—form what is ordinarily called the general circulation of the atmosphere. The migratory cyclones and anticyclones and the accompanying upper-level troughs and ridges, and at lower latitudes the tropical hurricanes, are usually classified as secondary circulations. There is not complete agreement, however, as to how the general circulation should be defined; I personally prefer to regard at least the existence of cyclones and anticyclones, and some of their collective statistical properties, as basic characteristics of the general circulation.

Having noted some of the principal features of the circulation of the atmosphere, let us see to what extent they can be accounted for. We shall first examine some features of global scale. Proposed explanations for the trade winds date back several centuries, but Hadley (1735) was the first to recognize the significance of the earth's rotation, and his ideas have become a familiar part of meteorological history.

Hadley assumed that the excess solar heating in lower latitudes over that in higher latitudes would bring about a general rising motion in lower latitudes and sinking in higher latitudes, the circuit being completed by a general equatorward motion near the earth's surface and a poleward motion aloft. He argued that there would be no reason for systematic eastward or westward motion if the earth were not rotating. He noted, however, that the surface of a rotating earth moves more rapidly toward the east in low latitudes than in high latitudes, in an absolute sense. Air moving directly equatorward across some middle latitude would therefore, in trying to conserve its absolute eastward velocity, arrive at lower latitudes with a westward motion relative to the earth—thus the trade winds.

Hadley's numerical calculations indicated that the air would acquire much higher westward speeds than those actually observed, and he attributed the lower speeds to the frictional drag between the air and the earth's surface. He then noted that this same drag would continually slow down the rotation of the earth, unless counteracted by an equal and opposite drag somewhere else; this he assumed to occur in the latitudes of the prevailing westerlies. To account for the westerlies he argued that the air which had reached low latitudes and risen to higher elevations would, upon returning poleward, acquire an eastward motion relative to the earth, thus becoming the upper-level westerlies. Upon sinking in higher latitudes it would form the prevailing westerlies, after which it would again move equatorward, completing the circuit.

It is easy enough in the light of today's knowledge to find fault with Hadley's reasoning. For one thing, the equatorward or poleward moving air tends to conserve its absolute angular momentum rather than its absolute velocity, and Hadley's assumption to the contrary caused his numerical calculations to be too small by a factor of two. The tendency of the air to conserve its angular momentum is identical with what we now call the eastward component of the Coriolis force. But Hadley preceded Coriolis by a century, and it is perhaps to his credit that he was as nearly correct as he was. Moreover, his quantitative error does not invalidate his subsequent reasoning, which is entirely qualitative; his assumption concerning friction was simply that it would reduce the strength of the trade winds to what it is observed to be from what it would be otherwise.

A more general criticism of Hadley's work is that it fails to demonstrate that the circulation must assume its observed form in preference to some other, since it lacks the necessary quantitative treatment. It may be shown that in a thermally forced system the warmer air must rise and the colder air must sink in some over-all sense, or, more precisely, that the temperature and the upward motion must be positively correlated, but the correlation need not be perfect nor even very high. Hadley assumed, without justification, that all of the rising air was warmer than all of the sinking air, and his subsequent conclusions were therefore not demanded by the physical laws.

Nevertheless, as an essentially correct account of what does take place, as opposed to what must take place, Hadley's work went virtually unchallenged for nearly two centuries. Once the dynamical effect of the earth's rotation had been properly expressed in mathematical form (e.g., by Coriolis, 1835) it was possible to replace the qualitative reasoning by quantitative computations, and ultimately a number of theoreticians attempted to do so. As we have already noted, the exact equations proved to be so complex that numerous simplifications were required. Thus, as in Hadley's paper, the presence of oceans and continents was generally neglected. Within the framework of such simplifications, the early quantitative results (e.g., Oberbeck, 1888) generally confirmed Hadley's work.

We may reword Hadley's arguments concerning the frictional drag in terms of absolute angular momentum, by saying that angular momentum (regarded as positive if the motion is eastward) is transferred from the earth to the atmosphere in the latitudes of the trade winds, and from the atmosphere to the earth in the latitudes of the prevailing westerlies. Since the earth is to a large extent a solid, it does not acquire any differential rotation thereby, but the atmosphere, being a fluid, would continue to speed up (in the absolute sense) in low latitudes and slow down in high latitudes, were it not for some mechanism for conveying angular momentum from low to high latitudes within the atmosphere. Hadley's picture contains such a mechanism since the poleward moving air aloft carries with it more eastward angular momentum than the equatorward moving air below. Nevertheless, other mechanisms are physically possible.

A feature of Hadley's paper which was characteristic of much of the ensuing work is that the large-scale currents were assumed to behave quite independently of any secondary circulations. As one familiar with the high seas, Hadley was well aware of the violent storms which were often encountered, but he presumably looked upon them as irrelevant as far as the maintenance of the trade winds was concerned. Later investigators recognized the potential importance of the secondary circulations, but tended to regard them as a sort of large-scale turbulence, which could be suitably incorporated into the mathematical equations by choosing larger coefficients of viscosity and thermal conductivity than would otherwise be demanded. Since the appropriate values of these coefficients were not known in any case, the inclusion of storms would not invalidate any results which had been previously arrived at.

But sooner or later all theories are challenged, and Jeffreys (1926) eventually proposed that the secondary circulations were actually responsible for maintaining the global currents. This idea was not well received by those who based their reasoning upon turbulence theory; turbulence should tend to smooth out the temperature field by conveying heat from latitudes of high to those of low temperature; likewise, it should tend to create a state of solid rotation by conveying angular momentum from latitudes of high to those of low angular velocity. Jeffreys was proposing that, unlike turbulence, the secondary circulations conveyed angular momentum in the opposite direction.

For a number of years Jeffreys' ideas were no more than alternatives to Hadley's. Then, following World War II, Starr (1948) observed that upper-level troughs and ridges whose axes possessed a general northeast-southwest orientation were of the proper shape to convey angular momentum northward. In Figure 5 a ridge of this sort extends northeastward from the high-pressure center marked with an "X," in the lower right portion of the map. To the east of this ridge, the isobars intersect the 45th parallel nearly at right angles; the air therefore crosses the parallel from almost due north, and carries no angular momentum with it, except that which it possesses as a result of rotating with the earth. To the west of the ridge, the air crosses from the southwest rather than the south, and therefore carries considerable additional angular momentum. The result of this exchange of air across the 45th parallel is therefore a net removal of angular momentum from the south side to the north. Starr felt that throughout middle latitudes in the northern hemisphere, troughs and ridges of this shape were more prevalent than their mirror images, which would transport angular momentum in the opposite direction.

By 1950 routine upper-level wind observations in the northern hemisphere were of sufficient quantity and quality to put Starr's ideas to test. The calculations clearly indicated that the secondary systems, and particularly the upper-level troughs and ridges, transported enough angular momentum across the 30th parallel to maintain the prevailing westerlies north of there against the dissipative effects of friction (Starr and White, 1951). A decade later southern hemisphere observations were plentiful enough to yield a similar result (Obasi, 1963). Thus Hadley's account of the circulation was finally overthrown, not because of any fatal error in his reasoning, but because it failed to agree with observations which after more than two centuries had finally become available.

Close to the equator Hadley's ideas fared better. Air does appear to rise near the equator, notably in the intertropical convergence zone, and move toward the poles aloft, but it generally sinks and returns equatorward while still in the subtropics. The resulting closed circuits, which are confined mainly to the equatormost thirty degrees of either hemisphere, and which can convey significant amounts of angular momentum across the 15th parallels, are now known as the Hadley cells. Across the 30th parallels, and into the regions of the prevailing westerlies, the required momentum transport is accomplished by other means—the secondary systems.

Does this revised picture of the circulation explain why the trade winds and the prevailing westerlies exist, and why they are found in their observed locations? I feel that it does not, even though it reveals the immediate cause. We have simply replaced the problem of explaining these currents by the equally formidable problem of explaining why the upper-level troughs and ridges assume the orientations which they do, rather than essentially north-south orientations without much transport of momentum. Before attacking this problem we must consider a more basic question: why do we have secondary circulations at all?

There are many contributing factors. For one thing, the oceans and continents and the mountains and plains are rather irregularly distributed over the earth, and any circulation temporarily showing no variations with longitude could not maintain such a condition. Nevertheless, theoretical studies aimed at determining the effect of the irregularities of the earth's surface indicate that the variations with longitude which they demand are far less pronounced than the variations actually observed. There should therefore be some other explanation.

Although some meteorologists (Eady, 1950) had previously suggested that the secondary circulations formed as a result of the instability of the circulation which would otherwise prevail, I feel that the meteorological world was first made aware of the significance of instability by a laboratory device best known as the "dishpan." The relevant experiments were performed at the University of Chicago in the early 1950's (Fultz, *et al.*, 1959). Although the complete apparatus was rather elaborate and expensive, one of the principal elements was an ordinary dishpan. This was placed on a rotating turntable and filled to a depth of a few centimeters with water. The pan was heated near its rim by a heating coil, and in some cases was cooled near its center by a spray of water from below. The dishpan was supposed to simulate a hemisphere of the earth, the heating and cooling simulated the heating and cooling of the atmosphere in equatorial and polar regions, the rotation simulated the rotation of the earth, and it was hoped that the resulting circulation in the dishpan would simulate the circulation of the atmosphere.

One feature of the atmosphere prominently lacking in most of the dishpan experiments was the irregularity of the bottom surface, which would have been needed to simulate oceans and continents, or mountains and plains. Within the limits of experimental control, the input was perfectly symmetric with respect to the axis of rotation, and one might have anticipated that the resulting circulation would be symmetric also.

Figure 6 shows a nearly symmetric circulation which developed in one experiment. The photograph is a time exposure of the free surface of the water, upon which particles of a tracer have been sprinkled; the moving particles therefore appear as streaks, and the lengths of the streaks indicate the speed of the flow. The camera rotates with the

FIG. 6. Motion at free surface of water in differentially heated dishpan rotating at 1.9 rpm, after statistically steady state has been attained. Radius 19.5 cm, depth of water 4.2 cm. Photo through courtesy of D. Fultz.

dishpan, so that only the motion relative to the pan is revealed.

There is a single large vortex, whose center is near the center of the pan. Altogether the flow bears considerable resemblance to the circulation envisioned by Hadley.

Figure 7 shows a circulation obtained in an experiment where the external conditions are the same as before, except that the turntable rotates more rapidly. Here the symmetry is gone, and in addition to one concentrated elliptical vortex there are troughs and ridges bearing considerable resemblance to those found on upper-level weather maps. There is a fairly well developed jet stream, indicated by the longest streaks, which extends fairly close to the rim at some longitudes.

Sometimes a dye is introduced into the water to reveal the circulation

FIG. 7. Motion at free surface of water in dishpan heated as in Figure 6, rotating at 3.8 rpm, after statistically steady state has been attained. Photo through courtesy of D. Fultz.

at greater depths. When troughs and ridges occur at the free surface, small vortices resembling the migratory cyclones and anticyclones on weather maps are frequently found below.

Thus a symmetric input sometimes brings about a symmetric flow, and sometimes not. The rather abrupt transition from the type of flow pictured by Hadley to the type of flow more closely resembling the true atmospheric behavior, as the speed of rotation passes some critical value, strongly suggests that the asymmetries, when they occur, are the result of instability. That is, symmetric flow appears to be a mathematical possibility for any rate of rotation, in the sense that it is a solution of the mathematical equations governing the flow. For the higher rates of rotation, however, it appears to be unstable; asymmetric disturbances of small amplitude superposed upon a symmetric flow would ultimately develop into major features of the circulation.

The phenomena of stability and instability play a fundamental role in many of the sciences. The transition from stable to unstable motion is typified by the spinning top, which continues to stand on its point if it spins rapidly, but falls over if it spins too slowly, even though a slowly spinning or even a stationary top standing on its point is a mathematical solution of the equations governing the motion of the top. There is thus an analogy between the spinning top and the rotating dishpan, one of the obvious differences being that whereas the top is unstable when it spins slowly, the dishpan is unstable when it rotates rapidly.

How about the real atmosphere? Is the presence of secondary systems an instability phenomenon? We have noted that some asymmetries are to be expected in any case, but that they need not be so pronounced as the asymmetries actually observed. It therefore appears likely that secondary systems of the observed intensity, and particularly the migratory ones, occur because simpler circulation patterns, although mathematically possible, are unstable.

This conclusion has gained further support from one of the most recent innovations in theoretical meteorology—numerical simulation of the circulation, first introduced by Phillips (1956). Numerical simulation is an outgrowth of another recent development–numerical weather prediction. Here one attempts to forecast the weather by solving the system of equations governing the behavior of the atmosphere. We have already noted that some approximations are essential; in particular, because the equations are nonlinear, numerical methods of integration must be used to obtain time-dependent solutions. The initial conditions represent the present weather, and the solution is extended over the range of the forecast—most frequently one or two days.

In numerical simulation the equations are solved by the same methods, but the initial conditions need not represent any known weather situation, and the solution is extended over a period of months or even years. The numerical solutions are then treated as data, and various statistics are computed from them. The investigator hopes that these statistics will be representative of the general solution of the equations, just as the climatologist hopes that the statistics which he computes from weather records will be representative of the long-term climate.

Figure 8 shows a particular sea-level weather map generated by Smagorinsky (1965) in his numerical experiments. As in the real atmosphere (Fig. 4), there is a nearly unbroken belt of trade winds in the lower latitudes, while the prevailing westerlies occur only in a statistical sense, and cyclones and anticyclones are abundant. Evidently the experiment does a creditable job of simulating the atmosphere.

The equations used in numerical simulation may be simplified to the extent of omitting all the inhomogeneities of the earth's surface, and suppressing the annual and diurnal variability of the heating. In this case steady-state symmetric solutions may be found numerically. Here there is no need to postulate that the symmetric flow is unstable; its stability may be tested by choosing initial conditions representing the symmetric flow plus a small asymmetric perturbation, and then solving the equations numerically. Within a few days the simulated circulation acquires secondary systems resembling those in the real atmosphere.

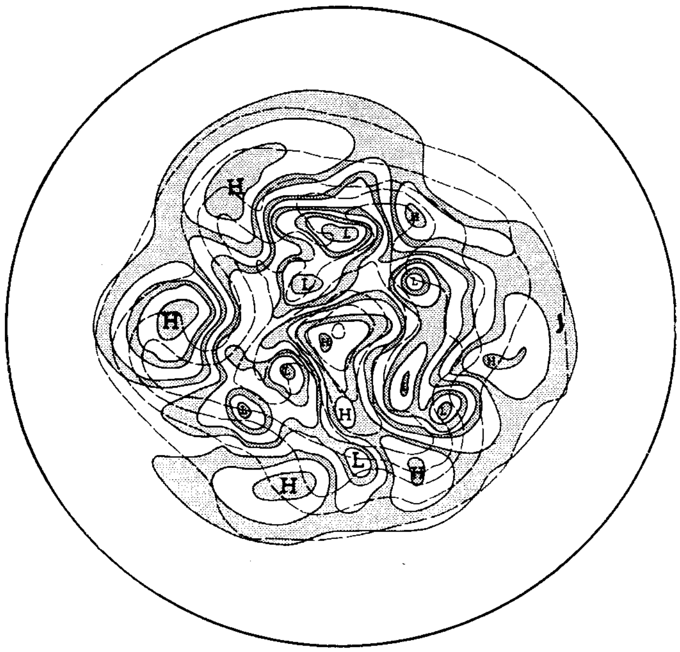

FIG. 8. Northern hemisphere weather map at sea level, generated in numerical experiment by Smagorinsky, *et al.* (1965). Shading is between alternate isobars, additional dashed lines are isotherms. Figure reproduced through courtesy of *Monthly Weather Review*.

I therefore feel that the existence of secondary circulations—the cyclones and anticyclones and the troughs and ridges—has been reasonably well accounted for. How can we now explain the preferred orientation of the trough and ridge lines, as we must if we are to explain the trade winds and the prevailing westerlies? I do not know of any simple qualitative arguments like Hadley's or any simple mathematical demonstrations which accomplish this end.

Nevertheless, in all the major experiments in numerical simulation of the circulation, the trough and ridge lines show a preference for the proper orientations, and the trade winds and the prevailing westerlies appear in the proper latitudes. In a sense, then, these global currents are explained; they are demanded by the system of equations which governs the atmosphere.

Some persons, however, would not find such an explanation very satisfying. They would argue that since the real atmosphere does obey the governing equations, and since trade winds and prevailing westerlies do occur, we know even without examining the equations that they demand the presence of trade winds and prevailing westerlies. To these persons the numerical experiments are little more than a demonstration that we are using realistic equations, and handling them properly.

Yet mathematical solutions do constitute acceptable explanations for many physical phenomena. What is lacking in this instance is a real physical insight into the mechanism through which the troughs and ridges acquire their typical orientation. If there is a simple process which could readily be described in a qualitative manner, it has so far been obscured by the complexity of the total problem.

Having satisfied ourselves reasonably well that the existence of middle-latitude cyclones is the result of instability, can we make the same statement about tropical hurricanes, which in some respects are so similar? It would be natural to assume that hurricanes develop because of the instability of the undisturbed trade winds, but we have yet to demonstrate that this is so. We have not shown that the low-latitude flow is unstable with respect to disturbances having the dimensions of tropical hurricanes, and hurricanes have not appeared in the numerical simulations of the total circulation. In this sense the simulations are less realistic than we should wish. Moreover, we are not sure why hurricanes do not appear.

A very promising recent suggestion (Ooyama, 1962; Charney and Eliassen, 1963) is that we are not properly taking into account the cumulus clouds which are present in the trade wind belts before a hurricane begins to develop. From the macroscopic point view, a mass of atmosphere filled with cumulus clouds is a different fluid from a mass of air which is either entirely saturated or entirely unsaturated with water vapor. In a cumulus-filled atmosphere a slight over-all increase in moisture does not cause a large unsaturated region to become suddenly saturated; it simply increases the percentage of the atmosphere occupied by the clouds, and reduces the spaces between the clouds. Our failure to simulate hurricanes numerically may thus arise because we are trying to make them develop in the wrong fluid.

Likewise, it is not known how great a role hurricanes play in maintaining the currents of larger scale. This lack of knowledge results largely from the lack of enough representative observations in the vicinity of hurricanes. Indeed, meteorologists who have been asked what would aid them most in furthering the purely theoretical study of hurricanes have frequently wished for more detailed observations. Evidently they have not expected to deduce the features which they have not yet observed. If we some day find that hurricanes are instrumental in maintaining the low-latitude circumpolar currents, just as the middle-latitude cyclones are instrumental in maintaining the prevailing westerlies, and if in addition we find that hurricanes cannot be properly explained without taking cumulus convection into account, we shall have established a close interrelation between three widely different scales of motion in tropical latitudes.

One of the most frequent complaints of the meteorologist is that much of the general public thinks of him as primarily a weather forecaster. A glance at such studies as the dishpan experiments or the computation of transports of angular momentum reveals that such a notion is ill founded. Nevertheless, the problem of weather forecasting does occur among the many problems faced by today's meteorologist, and I should like to conclude by saying a few words about it.

I have already mentioned numerical weather prediction. For forecasting in the one-day to one-week range, this powerful method seems destined to become more and more widely used, and it is well to note that certain limitations will nevertheless remain. Even the largest digital computer is a finite instrument, and the current state of the atmosphere must be represented by a finite collection of numbers, although it may be a large finite collection—perhaps 50,000 numbers. These numbers might be the values of four meteorological parameters—say temperature, two components of the wind, and water vapor content—at each of five elevations at each of 2500 geographical locations. Effectively the machine will then solve a system of 50,000 ordinary differential equations in 50,000 unknowns. Such a system might seem big enough for any physical problem.

But a total of 2500 points means that there is only one point for each 80,000 square miles of the earth's surface. Systems as large as the line of thunderstorms in Fig. 1 can easily lie hidden between these points, and may be represented very poorly or not at all.

Computers are becoming ever larger, but it is difficult to imagine one which can adequately describe the structure of every thunderstorm. It is equally difficult to imagine an observational network which will record the structure of every thunderstorm, even if the computer were large enough. Thus there will always be some uncertainty in the initial state.

We have noted that certain simple solutions of the governing equations are unstable. However, numerical simulations and theoretical considerations both indicate that all solutions of the equations are unstable; that is, two solutions originating from slightly different initial states will eventually evolve into considerably different states (Lorenz, 1963).

Now the state of the atmosphere as it is observed and recorded, and the state as it actually exists, may be regarded as two slightly different initial states. The predicted behavior and the actual behavior will therefore diverge from one another. Thus no method of forecasting can be expected to produce good forecasts for the far distant future.

The numerical simulations further indicate that small differences between the predicted and actual distributions of the weather elements may double in about five days, in the root-mean-square sense. This figure is highly tentative, but if it is correct we should some day be able to forecast a week in advance as well as we now forecast one or two days in advance. Forecasting the general trend of the weather may be possible at much longer range; for example, we may be able to say whether next summer will be a warm summer or a cold one. It seems most unlikely, however, that we shall ever make good weather forecasts for a particular day a month or more in advance.

REFERENCES

Charney, J. G., and Eliassen, A., 1963: On the growth of the hurricane depression. *Journ. Atmos. Sci., 21,* 68–75.

Coriolis, G., 1835: Sur les équations du mouvement relatif des systèmes de corps. *Journ. École Polytechn., 15,* 142–154.

Eady, E. T., 1950: The cause of the general circulation of the atmosphere. *Centenary Proc. Roy. Meteor. Soc.,* 156–172.

Fultz, D., Long, R. R., Owens, G. V., Bohan, W., Kaylor, R., and Weil, J., 1959: *Studies of thermal convection in a rotating cylinder with some implications for large-scale atmospheric motions.* Meteor. Monographs, Amer. Meteor. Soc., Boston, 104 pp.

Hadley, G., 1735: Concerning the cause of the general trade-winds. *Phil. Trans. Roy. Soc., 39,* 58–62.

Jeffreys, H., 1926: On the dynamics of geostrophic winds. *Quart. Journ. Roy. Meteor. Soc., 52,* 85–104.

Lorenz, E. N., 1963: The predictability of hydrodynamic flow. *Trans. New York Acad. Sci., Ser. 2, 25,* 409–432.

Obasi, G. O. P., 1963: Poleward flux of atmospheric angular momentum in the southern hemisphere. *Journ. Atmos. Sci., 20,* 516–528.

Oberbeck, A., 1888. Über die Bewegungserscheinungen in der Atmosphäre. *Sitzungsberichte Königl. Preus. Akad. Wiss.,* 383–395 and 1129–1138.

Ooyama, K., 1962: A dynamical model for the study of tropical cyclone development. *Bull. Amer. Meteor. Soc., 43,* 666.

Phillips, N. A., 1956: The general circulation of the atmosphere: a numerical experiment. *Quart. Journ. Roy. Meteor. Soc., 82,* 123–164.

Smagorinsky, J., Manabe, S., and Holloway, J. L., 1965: Numerical results from a nine-level general circulation model of the atmosphere. *Mon. Weather Rev., 93,* 727–768.

Starr, V. P., 1948. An essay on the general circulation of the earth's atmosphere. *Journ. Meteor., 5,* 39–43.

Starr, V. P., and White, R. M., 1951: A hemispherical study of the atmospheric angular-momentum balance. *Quart. Journ. Roy. Meteor. Soc., 77,* 215–225.