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The nature of the global circulation of the atmosphere: a present view

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SUMMARY

A current view of the global circulation is presented. It is proposed that without surface irregularities or variable heating there would be a mathematically possible steady-state zonally symmetric circulation. With the existing irregularities there still exists a circulation with no migratory cyclones or similar disturbances. These circulations are baroclinically unstable, whence the actual circulation contains fully developed large-scale migratory eddies.

The eddies receive available potential energy from the symmetric component of the circulation, and give up a smaller amount of kinetic energy. They transport large amounts of angular momentum across subtropical latitudes at high levels, thereby inducing direct meridional cells in low latitudes and indirect cells in middle latitudes, which help to maintain the trade winds and middle-latitude surface westerlies. The direct cells also carry large amounts of water vapour into low latitudes, thus producing the heavy equatorial rainfall. The accompanying release of latent heat supplies additional drive to the cells.

It is anticipated that a future view of the global circulation will include the solutions to some presently unanswered questions, but that interest will meanwhile shift to new questions posed by new ways of viewing currently available data and new types of data which will become available.

1. INTRODUCTION

It is with great pleasure that I face the privilege of presenting the opening paper at this distinguished gathering. Yet it is also with some apprehension, because I can recognize among the audience a number of outstanding scholars who have devoted much of their lives to the study of the global circulation of the atmosphere, and who certainly do not need to have the nature of this circulation explained to them now. I see some whose names have been well known for many years, whose papers I was required as a student to read, and whose opinions I have occasionally chosen to dispute. I see some who have more recently entered the field, who perhaps were required as students to read some of my papers and who on various occasions have taken exception to my ideas. Perhaps our main point of general agreement is that we consider the global circulation a suitable subject for continued study. Naturally we take the existence of a global circulation for granted.

Yet there must have been an age when man simply believed that the wind blows this way here and that way there. The concept of a global circulation where the manner in which the wind blows here is somehow connected to the manner in which the wind blows there, is presumably of more recent origin. It is clearly present in the famous paper of George Hadley (1735) concerning the cause of the trade winds.

Hadley observed that the general equatorward drift in the trade winds required a compensating poleward drift at higher elevations, in order to prevent a general accumulation of mass near the equator. He also noted that the general westward drag of the trade winds upon the earth's surface required a compensating eastward drag at higher latitudes, in order to prevent a general deceleration of the earth's rotation. Thus he was led to conceive of a global circulation whose various branches were interdependent.

Hadley opened his paper by stating, "I think the causes of the General Trade Winds have not been fully explained by any of those who have wrote on that subject," while, after presenting his own account, he stated, "Thus I think the NE winds on this side of the equator, and the SE on the other side, are fully accounted for." For some time Hadley's paper received little attention, but by the early nineteenth century the scientific world tended to accept his opinion that a full explanation had been offered. Subsequently it was realized that his dynamical reasoning possessed some flaws, which, however, did not invalidate his qualitative conclusions, but his account finally had to be rejected when it proved to be incompatible with newer observations.

In the ensuing years new accounts of the circulation were continually offered to meet the requirements of increasing observations and developing theory; these in turn were continually rejected as still more observations became available, or as still further theoretical results were established. The introduction of new observing systems and new theoretical techniques has not slowed down. It is my sincere hope that the thoughts which I shall present today will for the most part be accepted by many future generations. Nevertheless, I feel compelled to subtitle my talk 'a present view,' realizing that many aspects of the account may soon be discarded in the light of new observations, new theory, or simply new attitudes. Before presenting a detailed account, I shall outline the principal features of this present view.

The ultimate driving force for the circulation of the atmosphere is differential solar heating. The greater portion of the solar energy which is not reflected back to space is absorbed by the earth's surface rather than the atmosphere; this absorbed energy is in turn transferred to the atmosphere as sensible heat, or is used to evaporate water which subsequently condenses in the atmosphere and releases latent heat. The circulation arising from this heating is subject to frictional dissipation.

The principal driving force is the contrast in incoming solar energy between low and high latitudes. The resulting circulation acts to keep the cross-latitude temperature contrast smaller than it would be if no circulation were present, but it cannot remove it altogether. In accordance with the thermal-wind relation, the upper-level winds are primarily from the west, since, as Hadley noted, neither easterlies nor westerlies can predominate at the earth's surface.

For many purposes the real atmosphere may be approximated by an ideal atmosphere, where the incoming solar energy varies only with latitude, and the underlying surface of the earth is uniform in elevation and composition. There then exists at least one particularly simple atmospheric circulation pattern which is compatible with the heat sources and the surface geography; this circulation is completely symmetric with respect to the earth's axis and does not fluctuate with time. Its precise form is not known, but easterly surface winds predominate in low latitudes with westerlies in higher latitudes, and the meridional component is dominated by a large direct cell in each hemisphere. It possesses much in common with the circulation visualized by Hadley, and I shall refer to it as the *ideal Hadley circulation.*

Likewise, there is at least one particularly simple circulation pattern which is compatible with conditions which actually prevail. It bears considerable resemblance to the ideal Hadley circulation, but exhibits some variations with longitude because of the oceans and continents and other irregularities, and it varies with the hour and the season in response to similar variations in solar heating. However, it possesses no migratory storms or similar irregularities. I shall call it the *modified Hadley circulation.*

The modified Hadley circulation does not actually prevail in the atmosphere, nor would the ideal Hadley circulation prevail in an ideal atmosphere, because these circulations are unstable with respect to perturbations which vary with longitude; specifically, they are baroclinically unstable. The prevailing circulation therefore contains fully developed eddies; these are the migratory cyclones and other longitude-dependent systems.

The eddies are maintained against dissipative effects by receiving energy from the zonally symmetric component of the circulation; specifically, they receive available potential energy while, according to observations, they give up a smaller amount of kinetic energy. The removal of energy from the symmetric flow is balanced by the effects of heating and friction. It follows that if one could remove the eddies from the circulation pattern, while leaving the symmetric component just as it is, the system would no longer be balanced. The ideal symmetric circulation and the modified symmetric circulation are therefore not the same as the circulations which one would obtain by averaging the total circulations with respect to longitude, or time, or longitude and time.

In order to receive available potential energy from the symmetric circulation, the eddies must carry sensible heat toward colder latitudes. Likewise, in order to give up kinetic energy to the symmetric circulation, they must carry absolute angular momentum toward latitudes of higher angular velocity. For reasons which are not entirely clear, the transport of angular momentum is mainly poleward, and is strongest at high levels in subtropical latitudes. Accumulation of westerly momentum at high levels in middle latitudes and depletion in low latitudes, is prevented by a direct meridional cell in low latitudes in either hemisphere, which carries angular momentum upward, and an indirect cell in middle latitudes, which carries it downward, thus balancing the high-level horizontal momentum transport. Simultaneously the cells maintain trade winds and middle-latitude westerlies, stronger than would occur if the eddies were absent, against the effects of surface frictional drag.

The lower branches of the direct cells carry large amounts of water vapour toward the equator; this condenses upon rising in the intertropical convergence zone and yields the heavy equatorial rainfall. The accompanying release of latent heat enhances the intensity of the intertropical convergence zone and the direct cells which adjoin it.

It is apparent that some of the preceding statements are well supported by observation or theory. Others are largely speculative and may succumb to future observation or theory. Following a more detailed exposition of this present view, I shall therefore discuss some of the possible ingredients of a future view.

2. The search for the ideal Hadley circulation

Our detailed exposition of the global circulation begins not with what is, but with what might have been under somewhat different circumstances. The ideal Hadley circulation is not the circulation which prevails, and its precise configuration cannot be discovered through observation. Current attempts to investigate it are necessarily theoretical.

This was not always the case. In an earlier time it was believed that the ideal Hadley circulation and the general circulation were one and the same thing. Cyclonic storms and other intermittent irregularities were believed to be separately forced and were therefore considered irrelevant. Much of the circulation, particularly at high levels, was unobserved, and attempts to account for observed features, such as the trade winds, often went hand in hand with attempts to deduce the features which could not be seen. During this age the history of the search for the ideal Hadley circulation is synonymous with that of attempts to account for the general circulation.

The first account which appeared in its day to be complete is contained in Hadley's paper (1735). This remarkable work has become so well known that it scarcely needs recounting now, but we shall present it for subsequent comparison with other accounts. Hadley maintained that the greater solar heating in lower latitudes should lead to rising motion near the equator and sinking near the poles, with equatorward motion at low levels and poleward motion aloft completing the circuit. He then pointed out that air moving directly equatorward would, in attempting to maintain its absolute velocity, arrive at lower latitudes with a westward component, and appear as the trade winds. After being retarded by friction, rising, and proceeding poleward, it would arrive at higher latitudes with an eastward component, becoming the upper westerlies, whereafter, upon sinking, it would become the temperate westerlies before proceeding equatorward again. The meridional circulation which he visualized is shown schematically in Fig. 1.

Hadley did not realize that what we now call the east-west component of the Coriolis force is a manifestation of a tendency to conserve absolute angular momentum rather than absolute velocity, but this shortcoming does not affect his qualitative deductions. He was evidently unaware of the north-south component of the Coriolis force, and so assumed a meridional circulation similar to the one which would prevail if the earth were not rotating. Actually this meridional circulation is much too strong, yet again Hadley may have been qualitatively correct; there is no simple argument eliminating the possibility of a single direct cell in each hemisphere, with or without the earth's rotation.

For many years Hadley's paper remained virtually unnoticed. Even as it was gaining rather general acceptance, nearly a century later, new observations were beginning to

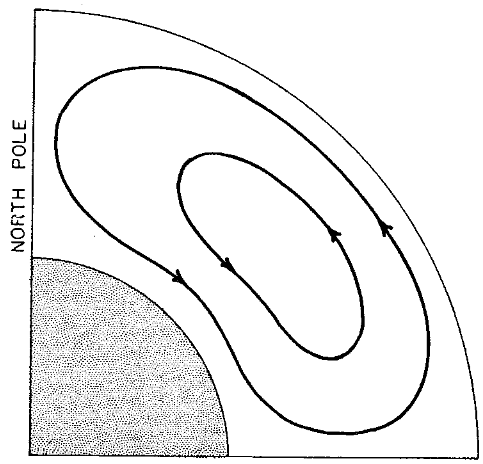

Figure 1. Schematic representation of the mean meridional circulation in one hemisphere, as visualized by Hadley (1735).

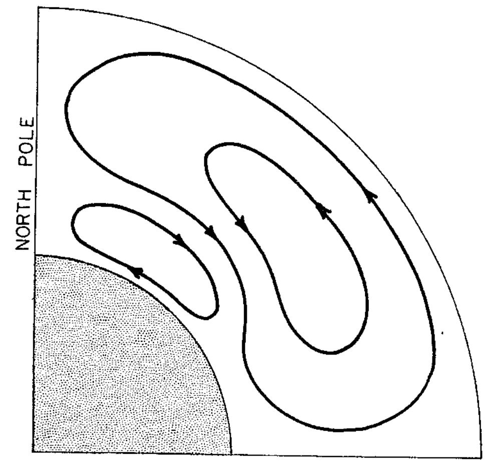

Figure 2. Schematic representation of the mean meridional circulation in one hemisphere, as visualized by Thomson (1857) and Ferrel (1859).

contradict it. It appeared that the air in the middle-latitude westerlies drifted slightly poleward, rather than equatorward as in Hadley's account.

There followed various attempts to replace Hadley's scheme by one which conformed to the newer observations. Of these, the only early accounts at least as rational as Hadley's were those of Thomson (1857) and Ferrel (1859). In their rather similar schemes, a large direct cell like Hadley's occupied the bulk of either hemisphere, but in middle and higher latitudes there was a shallow indirect cell, with poleward flow close to the ground and equatorward flow at an intermediate level. Their visualized circulation is shown schematically in Fig. 2.

Their explanations for the indirect cell invoked the north-south component of the Coriolis force, whose existence was just becoming recognized. They argued that in the belt of westerlies, the equatorward Coriolis force should be balanced by a poleward pressure gradient, whose existence was indeed verified by observations. Near the ground, however, friction would reduce the speed of the westerlies to the point where the accompanying Coriolis force would fail to balance the pressure gradient, and poleward motion would ensue.

Partly because Ferrel continued to publicize his ideas, but perhaps partly because the speed of communication had accelerated, Thomson's and Ferrel's schemes, unlike Hadley's, became fairly well accepted during the lifetimes of their originators, yet they too were doomed to suffer the same fate. As the nineteenth century ended, new observations were revealing that the high-level poleward currents, essential to the maintenance of upper westerlies in either scheme, did not extend beyond the 30th parallels.

The early twentieth century saw numerous futile attempts to construct meridional-circulation schemes which would fit the ever-increasing collection of observations, while still possessing no obvious dynamical impossibilities. Meanwhile, other writers were beginning to maintain that cyclones and other irregularities were by no means irrelevant and indeed, that the zonally symmetric component of the circulation could not be explained without taking them into account. This point of view was clearly stated by Bigelow (1902), but became more generally recognized following the works of Defant (1921) who maintained that the eddies transported heat to higher latitudes, and Jeffreys (1926), who proposed that they transported angular momentum. Once these notions became fairly well accepted, attempts to account for the general circulation could no longer be identified with the search for the ideal Hadley circulation; a specific piece of work might be directed towards one problem or the other, but not both. As the twentieth century progressed, the general circulation continued to attract attention, while the search for the ideal Hadley circulation approached a standstill.

Interest in the latter problem was revived, especially among theoretical fluid dynamicists, following the discovery by Fultz (1951) that certain laboratory experiments, designed to simulate the circulation of the atmosphere, would sometimes produce axially symmetric flow instead. Fultz's apparatus consisted of a rotating cylindrical vessel containing water, heated near the rim and cooled near the centre. Under certain conditions he obtained flow patterns possessing migratory waves and other irregularities. Under other conditions differing only in the rate of rotation or the intensity of the heating contrast, he obtained the laboratory equivalent of the ideal Hadley circulation.

Among recent theoretical studies of axially symmetric flows we mention one by Williams (1968). The flow occupies a cylindrical annulus rather than a spherical shell; however, to eliminate one of the dissimilarities between the atmosphere and the laboratory experiments upon which his study was modelled, Williams assumed the vertical walls of the annulus to be frictionless. He then solved the governing equations numerically, as an initial value problem, for various widths and depths of the annulus. Variations with longitude were not allowed to enter the solutions. In due time the solutions converged to steady states.

The meridional circulations which he obtained varied according to external conditions, but in general were like the one shown schematically in Fig. 3. A large direct cell dominates the flow, but indirect cells occur above and below it, while (in some cases) additional small direct cells occur above and below these. Such a flow pattern could conceivably have been proposed in the late nineteenth century, since it does not violate the observations which were then available.

An ideal Hadley circulation has also been found with some of the two-layer numerical models used to simulate the general circulation. These models, however, lack even the vertical resolution needed to represent Thomson's and Ferrel's circulation. We are not aware that an axially symmetric circulation has been determined with a multi-layer global or hemispheric model.

Without attempting to solve the problem at this point, let us examine more closely some of the considerations involved. First consider friction. We are probably not particularly interested in the solution which would result if only molecular friction were present.

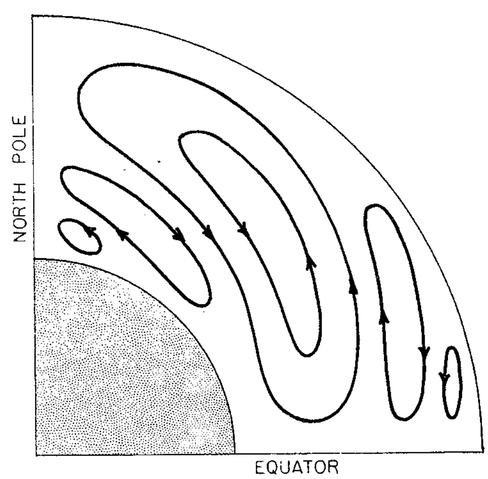

Figure 3. Schematic representation of the mean meridional circulation as determined numerically by Williams (1968). The computations were for a rotating cylindrical annulus with frictionless side walls, but the diagram is transcribed to a sphere for comparison with Figs. 1 and.

It would seem reasonable to use a coefficient of turbulent viscosity comparable to one generally used in Ekman-layer theory, perhaps 10^5 times the size of the coefficient of molecular viscosity. Presumably a comparable coefficient of turbulent conductivity would also be appropriate, in place of a molecular coefficient. In effect, the flow would be allowed to contain small-scale turbulent eddies; only the somewhat larger scales of motion would be required to be axially symmetric.

Since we are not admitting negative viscosity, as we might if we were attempting to parameterize large-scale eddies (cf. Starr 1968), there is no means for producing negative values of absolute angular momentum. Consider a region of the atmosphere containing the north (or south) polar axis, and bounded laterally by a surface of constant angular momentum; the latitude of this surface will vary somewhat with elevation. The meridional circulation cannot accomplish any net transfer of angular momentum across the boundary, while friction within the atmosphere, at least if it is effective mainly in the vertical direction, will transfer angular momentum into the region. It follows that surface friction must remove angular momentum from the region, i.e., the surface winds in the region must be predominantly westerly. Thus westerly rather than easterly surface winds must first be encountered as one leaves the pole; there can be no polar easterlies.

In working with an idealized atmosphere it would appear reasonable to choose a rather simple heat source. However, the resulting ideal Hadley circulation must depend critically upon this choice; conceivably one choice might lead to a circulation like Hadley's, while another might lead to one like Thomson's and Ferrel's. Perhaps the most satisfying procedure then, although certainly not the simplest, would be to assume a realistic geographical and spectral distribution of incoming solar energy. The re-radiation of energy would depend upon atmospheric conditions.

Much of the solar energy is absorbed by the earth's surface before being given up to the atmosphere. If the circulation is to be zonally symmetric, the surface will have to be all land or all ocean, or else the shorelines of the continents will have to lie along latitude circles.

The simplest thing would be to choose a land surface, and let the atmosphere be devoid of water. The net heating would then be vastly different from what we are accustomed to finding in the atmosphere, and as a consequence the circulation would probably appear so strange that we would not regard it as the circulation which we were seeking.

It would be more interesting to choose an ocean surface, and allow for the occurrence of a complete hydrological cycle, with evaporation, condensation and its accompanying release of latent heat, and precipitation. Clouds would then occur in bands surrounding the globe. At any given latitude it would be raining everywhere or nowhere. The clouds and rain would of course influence the reflection, absorption, and emission of radiation.

Presumably an intertropical convergence zone would form. Probably it would look somewhat like the one which actually occurs over the oceans, except that it would be active at all longitudes simultaneously. The circulation would perhaps be further complicated by a polar frontal surface, or some other internal surface of discontinuity. Almost certainly it would not be the simple circulation visualized by Hadley.

Determining the modified Hadley circulation which would be compatible with an irregular distribution of oceans and continents would be an even more difficult task. Perhaps it could be found by some successive approximation procedure, with the ideal Hadley circulation serving as the initial approximation.

3. Instability of the ideal Hadley circulation

As already noted, the ideal Hadley circulation and the general circulation were for a long time believed to be one and the same thing. When in the early twentieth century it became evident that cyclones and similar systems played a role in the general circulation, the problem of explaining the very existence of these systems assumed added importance. Among those pursuing the problem two schools of thought developed.

One of these maintained that an axially symmetric circulation was dynamically impossible; in essence, its proponents denied the mathematical existence of an ideal Hadley circulation. We cannot accept their contention. Looking back upon the various chains of reasoning which they followed, we find that at one point or another they took the geostrophic relation too literally. Certainly a symmetric circulation can have no eastward or westward pressure gradient, but this does not preclude a southward or northward wind component.

Yet in fairness to the ideas of this school, we should note that we have yet to *prove* the existence of an ideal Hadley circulation. The argument that a mathematical solution with axially symmetric initial conditions will remain axially symmetric is sound, but the solution could conceivably never settle down to a steady state.

The other school of thought maintained that while an ideal Hadley circulation existed, it would be unstable. A number of variations of this idea were offered, but the proper formulation appears to have first been given by V. Bjerknes (1937). Bjerknes regarded the schemes of Thomson and Ferrel as the only dynamically sound axially symmetric schemes so far proposed; however, these obviously did not agree with observations. Though not offering a proof that these circulations were unstable, he observed that they did not appear to be stable, and concluded that it was because of the instability of the circulation which would prevail if cyclones and similar systems were absent that such systems must appear.

The proof which Bjerknes failed to offer has still not been given. Not having found the ideal Hadley circulation, we cannot test it directly. It is of course possible to deduce certain properties of a flow pattern without determining the pattern in its entirety; perhaps one can show that the ideal Hadley circulation satisfies conditions for instability. To the best of our knowledge this has not been done.

Why, then, are we so willing to maintain that the circulation is unstable? First of all, there are numerical models of the general circulation which, although rather oversimplified, particularly in their vertical structure, nevertheless bear some resemblance to reality. In these the ideal Hadley circulation may be found and tested for stability. The original numerical experiment of Phillips (1956), for example, began by establishing the ideal Hadley circulation, and then perturbing it; cyclones were soon evident.

We are not aware that the nine-level model of Smagorinsky *et al.* (1965), for example, has been used in this manner. Since the grid points are not arranged along latitude circles, axially symmetric initial conditions without any disturbances cannot readily be introduced. Yet with approximately symmetric initial conditions, the ideal Hadley circulation, if it should be stable, ought to be approached. If it is unstable, its form will not be discovered, but its failure to develop will, in the context of the model, imply its instability. We feel so confident, incidentally, that the model would exhibit instability, that, if this proved not to be the case, we would look for a flaw in the model.

Further evidence favouring instability of the ideal Hadley circulation is to be found in the laboratory experiments. Here the transition from steady-state axially symmetric flow to irregular flow, as the rotation rate and the heating contrast are varied, is in good agreement with the theoretical stability criterion. Moreover, the flow patterns occurring in the experiments under unstable conditions are strongly suggestive of atmospheric patterns.

Small-amplitude disturbances superposed upon an unstable ' basic ' flow will in the course of growing acquire energy. Unless this energy is directly supplied by external forcing, in which case the stability or instability of the basic flow would be more or less irrelevant, the source of the energy must be the energy of the basic flow itself.

In considering basic flows which could conceivably occur in the atmosphere or other thermally forced rotating systems, we may distinguish between barotropic instability, where the disturbances receive kinetic energy from the basic flow, and baroclinic instability, where they draw upon available potential energy, specifically, the energy associated with horizontal temperature gradients. In the latter case, if the conditions for barotropic instability are not also fulfilled, the disturbances may give some kinetic energy back to the basic flow. To do so they must of course convert some of their own available potential energy into kinetic energy.

Even without horizontal temperature gradients, a basic flow may possess available potential energy if the temperature falls off rapidly enough with elevation. In this case small disturbances may also grow, but the instability is characterized as vertical rather than baroclinic instability. Vertical instability favours the growth of disturbances possessing comparable horizontal and vertical scales, while baroclinic instability favours large horizontal scales.

The axially symmetric circulations which have been produced with certain mathematical models are baroclinically unstable. Likewise, a baroclinic instability criterion separates the symmetric and unsymmetric flows produced in the laboratory. We may therefore infer that in the atmosphere the ideal Hadley circulation is baroclinically unstable.

Probably the circulation is also vertically unstable. That is, there are presumably at least a few regions with superadiabatic lapse rates, where small-scale disturbances will grow.

Suppose that small-amplitude disturbances of all scales are superposed upon the ideal Hadley circulation. If the circulation is baroclinically unstable but vertically stable, the larger-scale disturbances will become fully developed in a matter of hours or days. If, on the other hand, it is vertically unstable, the smaller-scale disturbances will reach their full development in the course of minutes. In so doing they will extract energy from the ideal Hadley circulation, and consequently alter its form, before the large-scale disturbances have undergone appreciable growth. Strictly speaking, then, the baroclinic instability of the ideal Hadley circulation would be irrelevant to the formation of cyclones and similar systems. What is relevant is the baroclinic instability of the total circulation which results when small-scale disturbances superposed upon the ideal Hadley circulation have grown to maturity. This circulation presumably possesses no appreciably superadiabatic lapse rates.

Further complications arise because of conditional instability, i.e., in approaching maturity the small-scale disturbances lead to saturation in certain regions, and the accompanying release of latent heat enables the disturbances to become far more intense than they otherwise would. The additional removal of energy from the ideal Hadley circulation tends to eliminate lapse rates appreciably steeper than the moist-adiabatic.

To a certain extent we acknowledged this state of affairs when we favoured the use of coefficients of eddy viscosity and conductivity far greater than the corresponding molecular coefficients, in seeking the ideal Hadley circulation. However, if the disturbances resulting from vertical and conditional instability are to be properly parameterized, the coefficients should depend somehow upon the lapse rate, or else superadiabatic lapse rates should be suppressed by a convective adjustment procedure such as the one formulated by Manabe and Strickler (1964).

Similar considerations presumably apply to the modified Hadley circulation, which is more relevant to the real atmosphere. Verification of the various hypotheses is correspondingly more difficult.

4. The nature of the eddies

If the ideal, or modified, Hadley circulation is indeed unstable with respect to perturbations of small amplitude, we can be sure that the existing flow will possess eddies of finite size. By this we do not mean that the existing eddies have originated from small-amplitude disturbances; we simply mean that the instability renders it impossible for eddies not to be generally present. If the eddies could somehow be suddenly removed, the remaining symmetric circulation, whatever its form, would soon acquire the form of the ideal Hadley circulation, whereupon new eddies would originate from small amplitude perturbations.

Just as a small disturbance requires an energy source if it is to grow, so a fully developed eddy requires an energy source if it is to be maintained. If an eddy could have developed from a small perturbation, regardless of whether or not it did develop in this manner, it is natural to assume that the processes which maintain it are similar to those which would have caused it to grow during its earlier stages. Thus, if it is superposed upon a barotropically unstable symmetric flow, we might assume that it receives kinetic energy from this flow, whereas, if it is superposed upon a baroclinically unstable flow, we might assume that it gains available potential energy.

Nevertheless, such assumptions cannot be established as general rules through theoretical reasoning, no matter how valid they may be in individual cases. First, by removing energy from a basic flow, a growing disturbance converts this flow into a different flow, with somewhat different properties. In the case of the atmosphere, if the disturbances gain energy from the symmetric flow, external processes must in the long run supply an equal amount of energy. If the disturbances could be permanently removed, while the external processes continued to supply energy at the same rate, there would no longer be an energy balance. Since the ideal Hadley circulation is a balanced system, it follows that this circulation and the axially symmetric component of the existing circulation are not one and the same thing. Early attempts to combine the dynamics of the ideal Hadley circulation with observations of the existing symmetric circulation were thus doomed to failure. Whereas the instability of the former assures us that eddies will exist, the properties of the latter are more relevant to the manner in which eddies are maintained.

Moreover, having reached finite size, a disturbance may act to deform its own pattern; witness the occlusion of an extratropical cyclone. It would not be surprising if a new symmetric flow should choose a new process to maintain disturbances of a new form. Even if the symmetric flow is no longer capable of maintaining any disturbances, a disturbance need not die out if it has acquired a capability of being maintained by external forcing. Thus, although we may anticipate that the eddies in the atmosphere will receive available potential energy from the symmetric flow, while perhaps giving up a smaller amount of kinetic energy, purely theoretical reasoning does not assure us that this is the case.

Fortunately we can turn to observations. These now reveal clearly that on the whole the eddies gain available potential energy from the axially symmetric flow, while they give up kinetic energy to it. Specifically, they transport sensible heat mainly toward latitudes of lower temperature, thus acting to reduce the cross-latitude temperature gradient, while they transport angular momentum predominantly toward latitudes of higher angular velocity, thus acting to strengthen the zonal flow where it is already strongest. Let us consider the nature of the eddies, as observed, in greater detail.

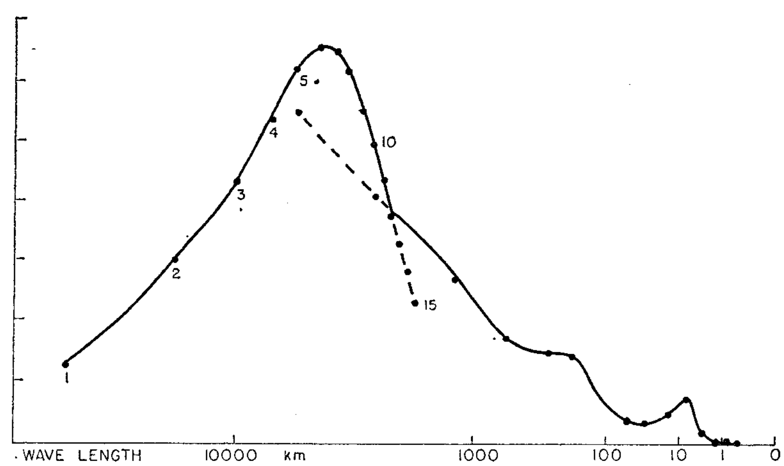

Figure 4. Spectrum of eddy kinetic energy in temperate latitudes. Left portion is based on work of Wiin-Nielsen (1967). Numbers indicate circumpolar wavenumbers. Right portion is based on work of Pinus, Shur and Vinnichenko (1967). Dots indicate wavelengths for which evaluations were made. Dashed segments are extensions of results of separate studies beyond point of intersection. Area under segment of curve is proportional to eddy kinetic energy in corresponding band of spectrum.

Fig. 4 is an estimate of the kinetic-energy spectrum of the eddies. It is drawn so that the area under any segment of the curve is proportional to the energy in that spectral band; the total area represents the total eddy kinetic energy, equal roughly to the value it would assume if the wind speed were 12 m sec^{-1} everywhere.

The curve is a composite one. The left-hand portion is based upon evaluations by Wiin-Nielsen (1967) who used wind values obtained from analysed upper-level maps. The right-hand portion is an average of values given by Pinus *et al.* (1967) who based their computations upon special rawinsonde ascents at two-hour intervals, and airplane flights. In both cases the data are from temperate latitudes and the shape of the curve may not be particularly representative of the tropics.

Even allowing for a high margin of uncertainty, it seems evident that the bulk of the energy is contained in wave lengths at least a few thousand kilometres long. Thus the principal energy-containing eddies are of the size which would be anticipated if they owed their existence to baroclinic instability. Eddies small enough to have arisen from vertical instability, while also present, are much weaker.

Fig. 5, which is related to the geographical distribution of the eddies, shows the standard deviation of the northward wind component as a function of latitude and elevation. It is based upon a diagram presented by Saltzman and Vernekar (1968). The evaluations were made directly from wind observations and so presumably include contributions from all portions of the spectrum, except wave lengths shorter than the distance travelled by the rawinsonde balloons between successive fixes. The bulk of the eddy energy is in middle latitudes, but the frequently heard statement that the tropical circulation is essentially zonal in character is not entirely borne out, especially at higher elevations.

The left portion of Fig. 6 shows the mean northward transport of sensible heat by the eddies for the northern hemisphere, as determined by Starr (1968) from five years of daily wind and temperature observations. The principal feature is a generally poleward transport, concentrated at rather low elevations. A secondary maximum occurs near the tropopause, while in the deep tropics the transport is mainly toward the Equator.

The left portion of Fig. 7 shows the mean northward eddy-transport of angular momentum, also determined by Starr (1968) from the same data collection. Here the outstanding feature is the maximum near the tropopause level, close to the 30th parallel. Weaker equatorward flow occurs at fairly high latitudes.

The left portion of Fig. 8 shows the northward eddy-transport of water vapour, as determined by Peixoto and Crisi (1965) from one year of data. Since this transport also

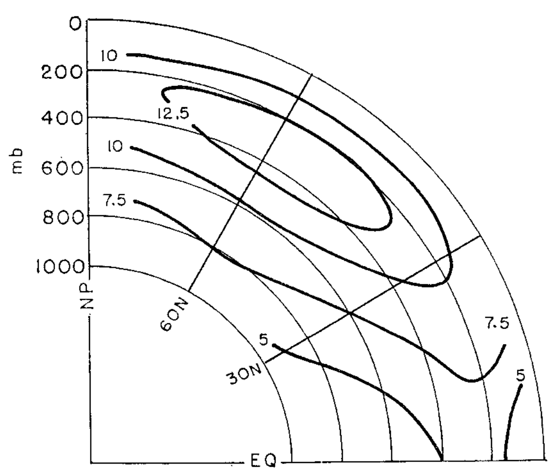

Figure 5. Annual mean standard deviation of northward wind component in m sec^{-1}, as given by Saltzman and Vernekar (1968).

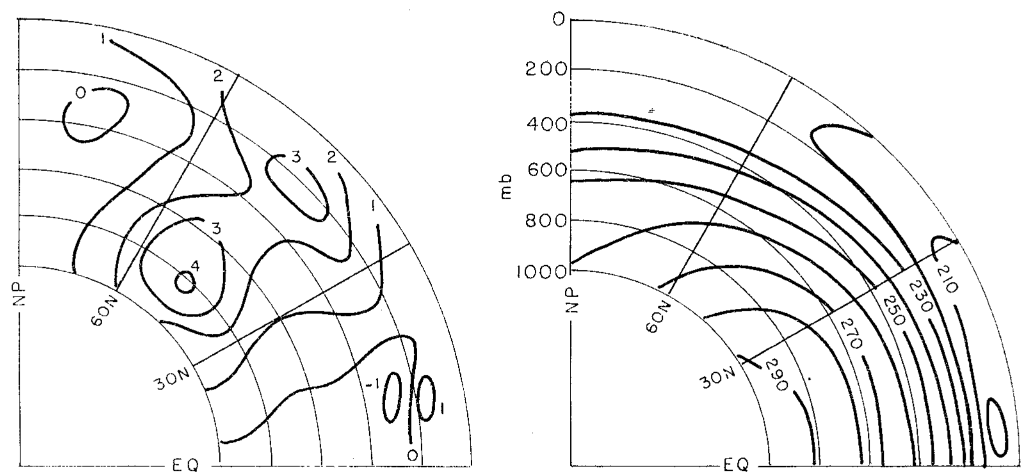

Figure 6. Annual mean northward eddy-transport of sensible heat (left), in units of 10^{14} watts per 100 mb layer, and annual mean zonally averaged temperature (right), in degrees K, as determined by Starr (1968).

implies a transport of latent heat of condensation it plays a similar role to the sensible-heat transport, in the energy balance. In general the patterns in Figs. 6-8 are qualitatively similar to earlier evaluations based upon smaller data samples (cf. Lorenz 1967). To the extent that they can be evaluated, annual mean southward transports in the Southern Hemisphere appear qualitatively like northward transports in the Northern Hemisphere.

Since the transport of angular momentum has been evaluated from observed winds rather than analysed maps, it presumably includes the contribution of most of the spectrum. It can be shown, however, that the transport is due mainly to the larger scales. In any band of the spectrum, the maximum possible angular momentum transport is limited by the kinetic energy. The contribution of the small scales, even if the eastward and northward components of the wind were perfectly correlated in these scales, could not match the

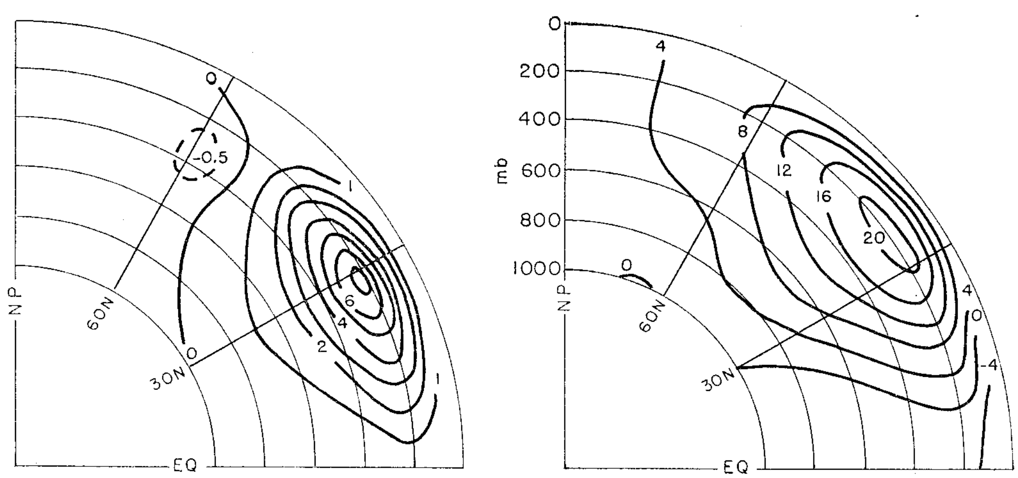

Figure 7. Annual mean northward eddy-transport of angular momentum (left), in units of 10^{25} g cm^2 sec^{-2} per 100 mb layer, and annual mean zonally averaged eastward wind component (right), in m sec^{-1}, as determined by Starr (1968).

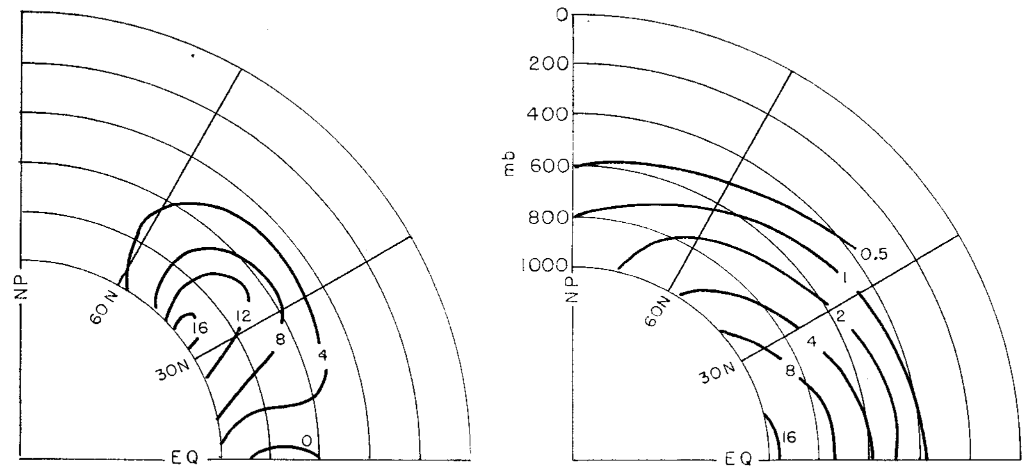

Figure 8. Annual mean northward eddy-transport of water vapour (left), in units of 10^{10} g sec^{-1} per 100 mb layer, and annual mean zonally averaged specific humidity (right), in thousandths, as determined by Peixoto and Crisi (1965).

observed contribution of the large scales, which results generally from correlations of about 0·2. Similar considerations apply to the transport of sensible heat, since the temperature spectrum has somewhat the character of the curve in Fig. 4.

These considerations do not apply to vertical transports. The vertical-kinetic-energy spectrum is difficult to evaluate, but there is no evidence that the energy is heavily concentrated in the larger scales. Typical updraughts and downdraughts in and between cumulus clouds, for example, are stronger than averaged upward or downward motions over cyclone-sized areas.

It is doubtful that the large-scale vertical-motion fields deduced by one means or another from more readily observable quantities are sufficiently accurate for evaluating reliable vertical transports of sensible heat, angular momentum and water vapour. Thus, even if we knew the small-scale contributions, we could not readily compare them with the large-scale contributions. However, it is easy to see how convective-cloud circulations can carry significant amounts of energy upward. Riehl and Malkus (1958), for example, have indicated that the entire vertical transport of energy in the equatorial zone could be accomplished by one giant cumulonimbus cloud per square degree – a not impossible number. Palmén and Newton (1969, Ch. 13) have indicated that significant amounts of angular momentum may also be transported vertically by cumulonimbus clouds, or by the squall lines into which these clouds are often organized.

Palmén and Newton (1969) have also evaluated the combined vertical transports by eddies of all scales as residuals needed to balance the remaining processes contributing to the budgets of angular momentum and energy. The vertical eddy-transport of angular momentum appears to be rather small, while that of energy is substantial.

5. The nature of the zonally averaged circulation

Given the horizontal and vertical eddy-transports of angular momentum and sensible heat, for a hypothetical dry atmosphere, or, in addition, the transport of water vapour, for a moist atmosphere, how can we deduce the zonally averaged fields of wind, temperature and moisture? The procedure is identical to that by which we can deduce the ideal Hadley circulation, except that the fields of convergence, or divergence, of the eddy transports of angular momentum, sensible heat, and water vapour appear as additional sources, or sinks, for the corresponding quantities. The problem therefore seems to be neither appreciably more difficult, nor easier, than that of deducing the ideal Hadley circulation.

The right portions of Figs. 6 and 7 show the mean zonally averaged fields of temperature and eastward wind component, as determined by Starr (1968) from the same five-year data collection used to evaluate the transports. Together these fields approximately satisfy the thermal-wind equation. The zonally averaged field of specific humidity determined by Peixoto and Crisi (1965) appears in the right portion of Fig. 8.

By comparing the two portions of Fig. 6, we see that the sensible heat transport is mainly directed towards lower temperature. Exceptions occur in the lower stratosphere and the tropical troposphere, but the net conversion of available potential energy is from the zonal to the eddy form. In Fig. 7 the main centre of angular-momentum transport lies somewhat south of the maximum eastward wind velocity, which in turn is slightly south of the maximum angular velocity. Up-gradient transports thus predominate over down-gradient transports, and kinetic energy is converted from the eddy to the zonal form. The energy cycle of the eddies is therefore qualitatively similar to that of incipient disturbances superposed on certain baroclinically unstable flows.

Within the tropics the eddies appear to give up both available potential energy and kinetic energy to the symmetric flow, and a question arises as to how they are maintained. The tropical atmosphere is not a closed system and the disturbances in it could conceivably be induced by middle-latitude disturbances. However, hurricanes and also weaker systems do not bear any easily recognized relation to the middle-latitude circulation, and it seems likely that they are fed by another source, namely, the release of latent heat of condensation. This condensational heating occurs mainly in small-scale convective clouds; it will, however, produce large-scale eddy available potential energy if the clouds favour the warmer parts of the eddies.

In dealing with the energy cycle of the atmosphere it is often convenient to treat the release of latent heat as one form of external heating (cf. Lorenz 1967, Ch. 5). The tropical disturbances would then be considered to be externally forced. Logically, however, condensational heating is an internal process, its intensity at any point depending mainly upon the local state of the atmosphere. If it selectively favours the warmer portions of disturbances, the growth of these disturbances ought to be ascribed to some form of instability, in which some form of energy, perhaps an 'available latent energy,' is converted from the zonal to the eddy form. This is evidently the form of instability which Charney and Eliassen (1964) have described as 'conditional instability of the second kind' in their study of the growth of hurricanes. Energetically, it seems to bear the same relation to baroclinic instability which ordinary conditional instability bears to vertical instability.

Our identification of the temperature, wind and moisture fields in Figs. 6-8 as those required by the accompanying transports of sensible heat, angular momentum and water vapour should not be taken to imply that the transports are entirely causes and the zonal averages are entirely effects. On the contrary, each exerts its influence upon the other. The atmosphere simply chooses a set of zonally averaged fields and a set of transport processes which are compatible with one another.

On the other hand, we feel, although we cannot conclusively demonstrate, that the transport of angular momentum is a cause rather than an effect of the trade winds and middle-latitude surface westerlies. The layers where these winds prevail constitute a rather small fraction of the atmospheric mass and contain an even smaller fraction of the kinetic energy. By themselves they probably do not exert a major influence on the momentum transport. The upper-level westerlies presumably exert a much greater influence, and these winds would occur with nearly their present strength, even with a different distribution of surface winds, as long as a poleward temperature gradient of the present magnitude prevailed. We suspect that a vastly altered upper-wind pattern would be needed to maintain eddies which would transport angular momentum equatorward.

A knowledge of the momentum transport alone will yield a reasonable first approximation to the meridional component of the zonally averaged circulation. Angular momentum is carried from low to middle latitudes mainly at high levels, but it can be added to the tropics and removed from higher latitudes only by surface effects. Some mechanism for an upward transport within the tropics and a downward transport at higher latitudes is needed, and the eddies do not appear to be equal to the task. If we assume that the meridional circulation is precisely that meridional circulation needed to accomplish the vertical redistribution of angular momentum, we find that there is a direct ' Hadley ' cell in low latitudes and an indirect ' Ferrel ' cell in middle latitudes in each hemisphere, the separations between the cells occurring at approximately the latitude of the maximum transport. A very simple procedure introduced by Mintz and Lang (1955) yields the quantitative first approximation.

Moreover, the momentum transport may be looked upon as the cause of the meridional circulation, which in turn is the most immediate cause of the trade winds and middle-latitude surface westerlies; if the meridional circulation were absent, the accumulation of angular momentum in higher latitudes, and the depletion in lower latitudes, would soon lead to unbalanced forces which would set the meridional circulation in motion again, although it might then undergo many oscillations before approaching a steady state. Likewise, the weaker equatorward momentum transport across higher latitudes tends to intensify the Ferrel cell, while causing a weak direct cell in polar latitudes, and ultimately leading to the production of weak polar easterlies, which, as we have noted, could not exist in the absence of eddies.

To realize that the procedure for deducing the meridional circulation is an approximation, we need only visualize the result of applying it to the case of no eddies. The result would be not the ideal Hadley circulation, but *no* circulation. The existing meridional circulation is presumably much stronger than the ideal Hadley circulation, except perhaps near the Equator, and the error in deducing it from the momentum transport is comparable in magnitude to the ideal Hadley circulation itself.

Fig. 9 shows two estimates of the northern hemisphere meridional circulation by Starr (1968). The former estimate, which is shown in the reference cited, is based upon five years of northward-wind-component data at about 700 stations; the latter is a revision using an additional 100 stations, mainly in the tropics. The Hadley and Ferrel cells and a weak second direct cell appear in both estimates. The latter estimate is felt to be more reliable, but the difference may be simply a measure of the uncertainty involved in estimating the meridional circulation from even to-day's data. For the Southern Hemisphere more

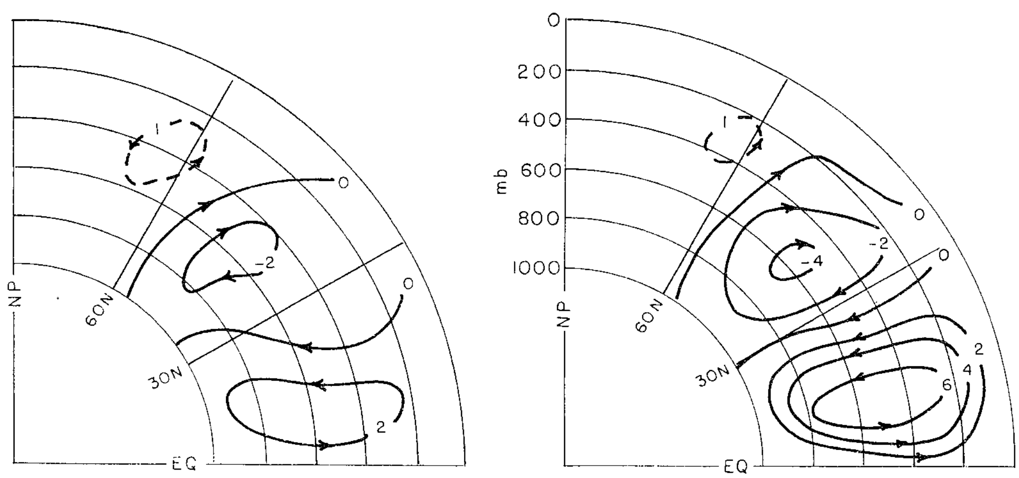

Figure 9. Stream function for annual-mean mean meridional circulation (left), in units of 10^{13} g sec^{-1}, as determined by Starr (1968) from five years of northward-wind-component observations at 700 stations, and revised estimate (right) when similar observations at 100 additional stations are included.

reliable results are still obtained by deducing the circulation indirectly from the angular-momentum transport, as has been done by Gilman (1965). The patterns in the two hemispheres are rather similar.

Although the meridional circulation possesses very little kinetic energy, its influence upon the total circulation is profound. The Hadley cells contribute to the immediate maintenance of the trade winds, in very much the manner which Hadley visualized, although they in turn are not maintained in the manner which Hadley assumed. They also carry significant amounts of sensible heat from low latitudes. Perhaps their most important function is to carry large amounts of water towards the Equator from either hemisphere, which they are able to do very effectively, since the atmospheric water vapour is concentrated in the lowest layers, where the strongest equatorward flow occurs. The water vapour subsequently condenses in the rising branches of the cells, largely in the intertropical convergence zones, and yields the heavy precipitation characteristic of equatorial regions.

A further effect of the condensation is the release of latent heat; this acts to increase the buoyancy of the rising air, and thus to render the Hadley cells more intense than they would otherwise be. This process plays a central role in a recent study of the intertropical convergence zone by Charney (1969). Thus it appears that the transport of angular momentum across subtropical latitudes at high elevations has far-reaching ultimate effects upon the circulation at other elevations and latitudes.

6. A FUTURE VIEW

If the present view of the general circulation as we have offered it differs considerably from the accepted views of a generation ago, so the view of a future generation may be expected to differ from ours. In the first place, there are obvious gaps in our present theoretical account which should eventually be filled.

We still have not, for example, discovered the pattern of the ideal Hadley circulation. Possibly all that is needed is a repetition of the work of Williams (1968), with a spherical earth, a compressible atmosphere, and a more realistic distribution of heating. If so, there is nothing to prevent this from being accomplished in the immediate future.

However, an attempt of ours to do just this did not succeed. Choosing a simple heat source, and starting with simple initial conditions, we found that in due time the solution appeared to be converging toward a steady state, but before the nature of this state could be ascertained, the solution began to diverge again. Moreover, the divergence was most evident in equatorial latitudes.

This strongly suggests to us that the ideal Hadley circulation is unstable with respect to *axially symmetric* perturbations and that the instability is somehow related to the spherical shape of the earth. If this is the case, we shall have to revise our account of why eddies must occur; they are required not simply because the ideal Hadley circulation is unstable with respect to eddy perturbations, but because, in addition, the time-variable but statistically steady axially symmetric circulation which would develop from the growth of axially symmetric perturbations on the ideal Hadley circulation is also unstable with respect to eddy perturbations.

Meanwhile, an initial-value method is simply one special successive-approximation procedure. It seems likely that other successive-approximation procedures may converge, regardless of stability or instability. We feel confident that the future view of the general circulation will include a picture of the ideal Hadley circulation.

A more formidable theoretical problem is that of explaining the strong poleward eddy-transport of angular momentum at high levels in subtropical latitudes, which, according to our present view, determines in a large measure the character of the general circulation. This is not the same problem as that of explaining why the eddy transport is predominantly toward latitudes of higher angular velocity, thus converting eddy kinetic energy into zonal kinetic energy. A strong southward transport of angular momentum (in the Northern Hemisphere) centred somewhat north of the maximum zonal westerlies would be just as effective as the existing arrangement in converting eddy to zonal kinetic energy, while a northward transport centred somewhat north of its actual location could convert zonal to eddy kinetic energy. Something in addition to energetics is involved.

Let us first note that when large numerical models of the atmosphere, such as the nine-level model of Smagorinsky *et al.* (1965), are used to simulate the general circulation, the transport of angular momentum in middle latitudes proves to be poleward, with about the proper magnitude. This strongly suggests that the proper explanation for the poleward transport does not involve some mysterious force or atmospheric constituent which has been neglected, but is contained in the dynamic equations as we ordinarily express them. Apparently the various theoretical attacks on the problem have started off with the right basic physical principles.

These theoretical studies have tended to adopt one or other of two somewhat divergent lines of approach. One may be called the *wave motion* approach, the other the *turbulence* approach.

In the wave motion approach an attempt is made to approximate the relevant features of the general circulation by moderately simple analytic functions. Frequently an analytic description of the zonal flow is chosen. The zonal flow invariably proves to be unstable with respect to eddy perturbations if the choice is realistic, and the form of the most rapidly amplifying normal mode is sought. The normal mode is often found to be suitably shaped for transporting angular momentum poleward across middle latitudes.

Under the assumption that fully grown eddies will have the same shape as the most rapidly growing incipient eddies, a complete picture of the circulation is obtained. This procedure has been exploited by Charney (1959), for example. The otherwise undetermined amplitude of the eddies can be obtained by requiring the energy cycle to balance. The question remains as to whether an explanation has been offered, or whether one may now justifiably ask, " Why does the most rapidly growing normal mode have this shape? "

Another variation assumes that the eddies originate with more or less randomly distributed shapes, perhaps through baroclinic instability, but are then deformed by barotropic processes. This approach was used by Kuo (1953) who found that poleward transports of angular momentum should develop. Most recently it has been exploited by Saltzman and Vernekar (1968) who obtain remarkably realistic horizontal and vertical distributions of momentum transport.

Yet the wave-motion studies introduce a number of assumptions whose main justification seems to be that they sometimes give good results. Moreover, the several waves surrounding the globe are assumed to be identical in shape, and, once they are fully grown, not to change their shape. Observed patterns, on the other hand, often contain some waves which transport momentum equatorward, together with those which transport it poleward. Even the net transport may be equatorward for periods of as long as a week. The poleward transport is essentially a statistical residual. The wave-motion approach thus oversimplifies the patterns which it attempts to explain.

The turbulence approach does not seek the forms of individual eddies, and considers only their statistical properties. Generally the eddies are assumed to behave like classical turbulence in that they transport some quasi-conservative quantity toward latitudes where this quantity possesses lower values, thereby acting to distribute the quantity more uniformly.

It has been generally accepted since the appearance of Defant's famous paper (1921), and it is now borne out by observations, that the large-scale eddies act mainly to smooth out the zonally averaged temperature field. They do not, however, act to smooth out the field of motion; it is well established that throughout much of the atmosphere they tend to produce rather than destroy zonal kinetic energy, and thereby give rise to a sort of negative viscosity (cf. Starr 1968). Thus a simple turbulence approach does not explain the transport of angular momentum. Recently Green (1969) has proposed that the quantity whose distribution the eddies act to equalize is potential vorticity which depends upon both the motion and the temperature fields, and is more nearly conservative than any quantity depending upon the motion alone. Possibly future computations will show this idea to be valid.

We must admit, however, that we see no particular reason why the transport of an arbitrary quasi-conservative quantity by atmospheric eddies should be directed toward lower values of this quantity. If, in spite of systematic transports by the eddies, the contrast in this quantity between latitudes and the contrast within latitudes, do not progressively change, there must be sources and sinks for the quantity. The conclusion that the eddies act to reduce the cross-latitude contrast evidently presupposes that the sources for the *contrast* are zonally distributed, while the sinks are distributed within zones. This is generally true in the case of the temperature contrast, whose principal source is the cross-latitude heating contrast. In the case of vorticity, which is perhaps the most nearly conservative quantity depending upon the motion field alone, large contrasts are introduced *within* latitude bands through baroclinic effects. What the situation is with regard to potential vorticity we are not prepared to say.

We feel that the large-scale eddies in the atmosphere are neither as smooth as normal-mode waves nor as random as turbulence. They are an intermediate phenomenon, which is more difficult to treat than either extreme. They can be treated numerically, and in a sense the results of the large numerical experiments constitute theoretical explanations. Yet it is hard to accept them as enlightening answers to " why " questions.

What we wish is a straightforward qualitative explanation for a qualitative phenomenon. We have in mind an account like the one presented by Fleagle (1957) who describes how the eddies ought to be deformed into the proper shape for accomplishing the momentum transport. His account is admittedly oversimplified since he treats separate latitudes independently, yet much of the proper explanation may be present. We have confidence, perhaps without sufficient justification, that the problem of explaining the angular-momentum transport will be solved in the coming years, as will other theoretical questions which are yet to be answered.

Does this mean that the coming generation will regard the general circulation as a solved problem? We believe otherwise. Opinions as to what constitutes the general circulation have never been static. A considerable shift of emphasis is anticipated in the years to come.

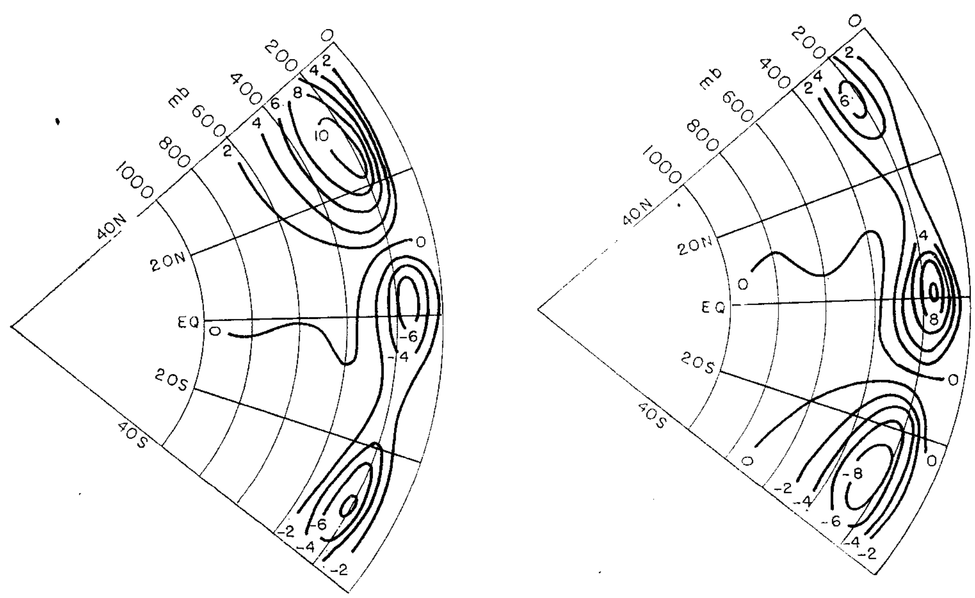

Figure 10. Northward eddy transport of angular momentum for December-February (left), and June-August (right), in units of $10^{25}\,g\,cm^2\,sec^{-2}$ per 100 mb layer, as determined by Kidson, Vincent, and Newell (1969).

First, we feel that the study of zonally averaged wind, temperature, and moisture fields, or zonally-and-time averaged fields, is already enjoying its golden age. The next generation may fail to see as much relevance in these fields as we do. Undoubtedly they are of prime importance if they can also serve as good first approximations to the fields to be found at specific instants. In the past we have supposed that while they may not serve this purpose in middle latitudes, they do so, by and large, in the tropics. Recent evidence fails to bear this out.

In Fig. 10 we present the fields of northward angular-momentum transport for the extreme seasons of the year, as evaluated by Kidson *et al.* (1969). In the spring and autumn (not shown in Fig. 10) the fields look rather like the annual mean field appearing in Fig. 7, but in each extreme season there is a strong transport across the equator toward the summer hemisphere comparable in magnitude to the transports across middle latitudes.

It might be expected that these transports of angular momentum would lead to meridional circulations differing considerably from the annual mean. Such is evidently the case. Fig. 11 shows the mean meridional circulations in the extreme seasons as determined by the same authors. As in Fig. 9, the circulations were evaluated from data for the northward wind component.

In the spring and autumn (not shown in Fig. 11), the meridional circulation resembles the annual mean, with well-developed Hadley and Ferrel cells in either hemisphere. In the extreme seasons, the Hadley cell of the winter hemisphere becomes enlarged and pushes into the summer hemisphere, which is perhaps not surprising in view of the well-known tendency for circulation features to move northward and southward with the sun, but the summer-hemisphere Hadley cell *disappears altogether*.

The immediate conclusion is that averaging over the entire year obscures many of the more interesting features of the circulation. Yet this well-known fact should not detract from the relevance of longitude-and-time averages if, as has often been done, the averages are confined to specific seasons and, possibly, specific times of day.

When, however, we ask what features are averaged together to make up the Hadley cell, or the absence of it, we recall immediately that at the extreme seasons an intense monsoonal circulation occupies the central longitudes of Asia. By and large there is a strong flow at lower elevations from well within the winter hemisphere to well within the

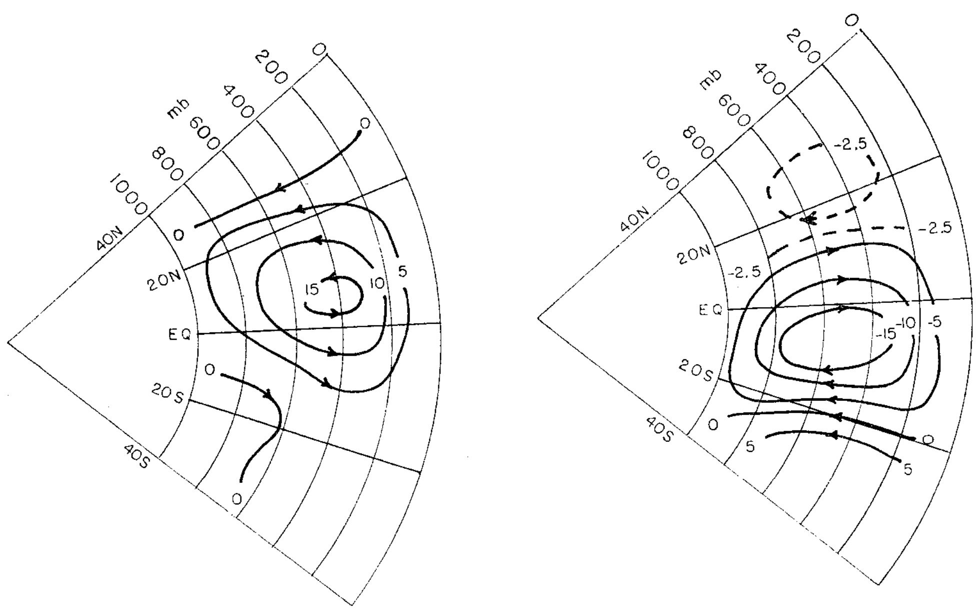

Figure 11. Stream function for mean meridional circulation in December-February (left), and June-August (right), in units of 10^{13} g sec^{-1}, as determined by Kidson, Vincent, and Newell (1969).

summer hemisphere. A return flow occurs at higher elevations. The general picture is complicated by such details as a jet-like current near the east coast of Africa.

Let us imagine that meridional motion of the type shown in Fig. 9, with a Hadley cell in each hemisphere, exists even in the extreme seasons, at all longitudes except those occupied by the Asiatic monsoon. Let us in addition visualize the result of averaging this rather weak Hadley-cell motion, extending perhaps four-fifths of the way around the globe, with a strong monsoon occupying the other fifth. The result would be a more intense Hadley cell in the winter hemisphere and a complete elimination of the Hadley cell in the summer hemisphere. This is precisely what is found.

The fact that the observed zonally averaged flow is similar to what would occur if the 'normal' pattern of a Hadley cell in either hemisphere prevailed everywhere except in the monsoon longitudes does not of course assure us that such a pattern does prevail. However, a hypothesis to this effect could easily be subjected to verification with presently available data.

It thus appears that by saying that the Hadley cell disappears from the summer hemisphere we may be completely obscuring the prevailing circulation throughout most of the tropics. At the same time we shall be overlooking the significance of the Asiatic monsoon. More generally, we may obtain a distorted idea of typical circulation patterns and overlook the processes which maintain these patterns by thinking primarily in terms of zonal averages and the cross-latitude transport processes which serve to maintain these averages.

In earlier days we were more concerned with systems – semi-permanent cyclones and anticyclones, for example. Efforts to explain the maintenance of these systems in sound mathematical terms often proved unrewarding. Zonally averaged quantities proved to offer more tractable problems and by shifting our attention to these we were able to establish positive results. Perhaps we are now approaching the time when we may redirect our attention to systems and deal with such problems as the maintenance of the principal jet stream, with all its meanders, as an entity, rather than simply the maintenance of the maximum in the zonally averaged wind field.

These new studies could presumably be pursued by processing already existing data in a new manner. We can visualize further shifts of interest which would result directly from the acquisition of new forms of data. Among the many outstanding products of modern technology available to the meteorologist, perhaps none is more spectacular than the high-resolution photographs of large areas of the earth, received every few minutes from the geosynchronous satellites. The principal features of these pictures are the cloud patterns, with their intricate structure on almost every scale.

The facts revealed by these pictures are too numerous to list. Already they are leading us to revise our ideas concerning the organization of the tropical atmosphere. A regular feature, for example, is the occurrence of cloud clusters extending over several degrees of longitude and persisting for a day or longer. When photographs taken on several successive days are averaged together (see Kornfield *et al.* 1967) the clusters in the Pacific Ocean sector often form two bands, one on either side of the equator. These may be interpreted as two intertropical convergence zones; the clusters are evidently identifiable with the more active regions of these zones.

Individual details may frequently be identified on successive photographs. By observing their displacement it has proved possible to deduce the wind field at cloud level over regions where conventional wind observations are scanty. It has even been possible to observe the spreading of cumulonimbus cloud tops contained in the cloud clusters, and thus to infer the extent of the updraughts within the cumulonimbi. This technique has been used by Sikdar (1969) to evaluate the vertical flux of energy occurring within the clusters. It appears from his work that cloud clusters may account for a major fraction of the vertical energy transport in the tropics.

Nevertheless, these studies are designed to yield the kind of data which we have already sought, or to answer questions which have already been asked. Future studies may address themselves to new questions.

There is a natural tendency to attribute increasing importance to phenomena with which we are continually confronted. It seems likely that as the cloud photographs continue to be part of our routine observational data, we shall become more and more interested in the cloud patterns for their own sake. Certainly the larger elements in the overall cloud picture are features of the general circulation.

There have been many studies of the balance of water vapour within various latitude belts or other regions, but who has made an observational study of the balance of *liquid* water (or ice)? The vast difference between the effects of liquid water and those of water vapour upon the radiation balance suggests that such a study will be far more than a curiosity. It will require new observations; today's radiosondes measure only the vapour phase of water. It will require new dynamical thinking; in most of the large numerical models, for example, liquid water is assumed to fall out as rain immediately upon condensation. Perhaps cloud photographs can supply the needed observations; certainly the dynamics can be worked out. Such a study would indeed centre upon clouds as the features of greatest interest.

The previous generation was greatly concerned with the dynamics of pressure systems and talked about highs and lows. Today we have not lost interest in these systems but we tend to look upon them as circulation systems. This change in attitude has led to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems.

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