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A STUDY OF THE GENERAL CIRCULATION AND A POSSIBLE THEORY SUGGESTED BY IT*

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Summary: A recently completed analysis of two years of data from two circumpolar chains of northern hemisphere stations, and one year of data from three additional chains, indicates that horizontal eddies transport as much angular momentum, water, and energy poleward as is required by the interaction of the atmosphere with its environment. The meridional circulations as measured transport minor amounts of angular momentum and water. The eddy flux of angular momentum is against the gradient of angular velocity throughout much of the atmosphere, so that kinetic energy is transferred from the eddies to the mean flow. The eddy flux of sensible heat is primarily with the temperature gradient, but is against the gradient in the lower stratosphere.

These results form parts of a possible theory of the general circulation. Other parts are suggested by various theoretical studies and by analogies with certain experimental models. It appears that the role of heating is to maintain available potential energy, represented primarily by the poleward temperature gradient. The resulting state is unstable, so that eddies appear. The potential energy of the mean flow maintains the eddies against dissipative effects, and the eddies maintain the kinetic energy of the mean flow against dissipative effects.

An extensive study has recently been completed by the General Circulation Project at the Massachusetts Institute of Technology, under the direction of Prof. VICTOR P. STARR. The principal results of this study have been prepared for publication by Prof. STARR and Dr. ROBERT M. WHITE[1]. The first portion of this presentation is concerned with the results of that study.

The study was based upon all available upper-wind and radiosonde observations, at standard levels up to 100 millibars, at five circumpolar chains of northern-hemisphere stations, during the year 1950, together with some low-latitude observations for 1949 and 1951. The five chains of stations were located approximately at latitudes 13, 31, 42·5, 55, and 70 degrees north, and each chain contained from ten to nineteen stations, with a total of 75 stations. The data were extracted directly from the coded messages, as published in the Daily Series Synoptic Weather Maps, prepared by the United States Weather Bureau[2] (1949 *et seq.*) in co-operation with the

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Army, Navy, and Air Force, and involved altogether a total of 176 thousand individual wind readings, 57 thousand humidity readings, and 77 thousand temperature readings.

Average values of certain quantities were computed from these data. The nature of the data renders short-period averages of doubtful significance, so that attention was given primarily to yearly averages and summer and winter averages. These quantities included the zonally averaged eastward and northward wind components, specific humidities and temperatures, and also the horizontal poleward fluxes of angular momentum, water, and total energy, as functions of latitude and elevation. The vertically averaged horizontal fluxes were compared with those required by considerations of continuity, as inferred from the best available estimates of the latitudinal distribution of exchanges of angular momentum, water, and total energy between the atmosphere and its environment.

The instantaneous local poleward flow of mass may be resolved into three components: the portion due to the long-period mean meridional circulation; the portion due to the additional instantaneous meridional circulation; and the portion due to large-scale horizontal eddy motion. Each of these components accomplishes a separate mode of poleward transport of any quantity. The transports of angular momentum and water were resolved into these three modes of transport, while in the case of total energy only the transport by horizontal eddies was computed.

The computations of the angular-momentum balance reveal the great importance of horizontal eddies, as compared to meridional circulations, in accomplishing the total transport across those latitudes where the transport is greatest. The transport by eddies appears sufficient to satisfy balance requirements, as determined from estimates of surface torques. The mean meridional circulation as measured possesses the familiar three-cell pattern, but most of the computed values are too small to be statistically significant in view of the nature of the data. The evidence against mean meridional circulations stronger than about one metre per second is fairly conclusive, except at low levels in the tropics, where a direct circulation stronger than two metres per second may occur in winter.

A further result is that the eddy flux of angular momentum is directed primarily toward latitudes of higher angular velocity. This counter-gradient flux results in a net conversion of the kinetic energy of the eddies into kinetic energy of the zonal flow, as has recently been pointed out by KUO,[3] and in more detail by VAN MIEGHEM[4].

The computations of the water balance again reveal the great importance of horizontal eddies, which transport sufficient water to satisfy the balance requirements, as estimated from evaporation and precipitation studies. The transport of latent heat of condensation which accompanies the transport of water accounts for at least half of the total necessary energy transport at subtropical latitudes.

The horizontal transport of total energy involves the transport of potential energy as well as sensible heat and latent heat. Since the potential energy per unit mass is very large at great heights, the transport of potential energy by the meridional circulation is greatly influenced by the nature of this circulation in the upper stratosphere, where sufficient data were unavailable.

Computations were therefore restricted to the transport of total energy by horizontal eddies, which do not transport potential energy. Again the eddies transport sufficient energy to satisfy the balance requirements, as inferred from radiation-balance figures. In lower latitudes the transport of sensible heat is not sufficient to satisfy the balance requirements, and the additional necessary energy is transported in the form of latent heat.

A further result is that the eddy flux of sensible heat is generally directed toward colder latitudes. However, in the lower stratosphere, the flux is against the temperature gradient, since the gradient is reversed, but the flux is still poleward.

This study makes it possible to present a comprehensive description of the processes which are responsible for maintaining the energy of the general circulation. Descriptions of certain of these processes have been appearing with increasing frequency in recent meteorological literature.

In discussing the energy of the general circulation, it is convenient to introduce the concept of available potential energy. This quantity may be defined as the difference between the total potential plus internal energy of the atmosphere, and the minimum potential plus internal energy which could result from any adiabatic redistribution of mass. This same quantity was described by MARGULES[5] in his famous paper concerning the energy of storms. The properties of available potential energy have been discussed in detail by the writer.[6]

Available potential energy may be expressed approximately in terms of a weighted vertical average of the horizontal variance of temperature. In this respect it bears a certain analogy to kinetic energy, which, aside from the contribution of the mean wind, depends upon the variances of the wind components. Just as the kinetic energy may be resolved into zonal and eddy kinetic energy, by an analysis of variance of wind, so the available potential energy may be resolved into zonal and eddy available potential energy, by an analysis of variance of temperature into the variance of zonally averaged temperature and the variance of temperature within latitude circles. Just as the rate of conversion of zonal into eddy kinetic energy depends primarily upon the eddy flux of angular momentum along the gradient of angular velocity, so the rate of conversion of zonal into eddy available potential energy depends upon the eddy flux of sensible heat along the temperature gradient. Zonal and eddy available potential energy may respectively be converted into zonal and eddy kinetic energy by meridional circulation and eddy motions.

The immediate effect of heating by the environment is the generation of zonal available potential energy, through heating in warm latitudes and cooling in cold latitudes. Crude estimates based upon the radiation-balance figures of ALBRECHT[7] indicate a generation of about 200×10^{20} ergs per second, or about two per cent of the total solar energy received at the outer limit of the atmosphere.

Since the horizontal eddy flux of sensible heat is primarily toward colder latitudes, there is a net conversion of zonal into eddy available potential energy, that is, the variance of temperature within latitude circles increases at the expense of the variance across latitudes. The rate of this conversion, estimated from the figures of the General Circulation Project, also appears to be about 200×10^{20} ergs per second.

Environmental effects probably destroy some of this eddy available potential energy instead of generating more, in view of the probable presence of heating of cold air masses and cooling of warm air masses at the same latitudes. However, some of the eddy available potential energy must be converted into eddy kinetic energy, since there is no other source for the latter, because, as we have seen, zonal kinetic energy acts as a sink for eddy kinetic energy. The rate of conversion from eddy to zonal kinetic energy is about 10×10^{20} ergs per second, according to the figures of the General Circulation Project (see STARR[8]). The rate of conversion from eddy available potential energy to eddy kinetic energy depends upon the correlation within latitude circles between temperature and vertical motion, and cannot be computed directly from available data. Presumably both forms of energy are destroyed by friction.

There remains the possible direct conversion of zonal available potential energy to zonal kinetic energy. However, the weak meridional circulation measured by Starr and White[1] leads to a conversion from zonal kinetic energy back to zonal available potential energy, at the rate of about 2×10^{20} ergs per second. The direction of this conversion results from the presence of the indirect cell in the latitudes of the strongest temperature gradient.

Now that we have established a picture of the energy cycle of the general circulation from the available observations, we may ask why the atmosphere chooses to operate in this particular fashion. In attempting to learn the answer, we shall be guided by the so-called 'dishpan' experiments being performed at the University of Chicago (see FULTZ[9], STARR and LONG[10]). In these experiments a circular cylindrical vessel containing water is rotated at a constant rate, and is subjected to uniform heating about the circumference and cooling at the centre. The flow of the water is observed by means of tracers.

Under sufficiently low rotation and sufficiently strong heating, the observed flow is nearly symmetric about the centre, and consists of a strong zonal flow with a weak superposed meridional circulation. Under faster rotation or weaker heating, the flow loses its symmetry, and exhibits meandering currents which bear a close resemblance to those found upon upper-level hemispheric weather maps.

The breakdown of the symmetric flow after a critical combination of rotation and heating is exceeded is suggestive of an instability phenomenon. Certainly the forced flow observed in the symmetric régime is dynamically stable. It seems possible that under supercritical conditions any forced flow will be dynamically unstable, in the sense that small superposed disturbances will grow until they become important features of the flow pattern. A study by the writer[11] appears to confirm this conclusion. Moreover, no tendency is revealed for the development of barotropic instability, that is, instability related to the horizontal distribution of vorticity. Instead, the instability seems to be baroclinic, that is, related to the temperature gradient and the accompanying vertical wind shear. Baroclinic instability increases with decreasing static stability (see CHARNEY[12]), and in this case seems to set in when the meridional circulation becomes too weak to maintain strong static stability.

On the other hand, the problem has been studied much more extensively by Kuo[13, 14], who has regarded the symmetric régime with its accompanying meridional overturning as a large-scale convective phenomenon. Heating tends to generate such convection, while rotation tends to suppress it. Thus Kuo finds that for sufficiently high rotation or weak heating, large-scale convection is impossible, that is, the heating cannot force any symmetric flow.

These studies may seem to represent different points of view, but the results are actually compatible, and together allow for one régime where symmetric flow will be observed, another régime where symmetric flow is mathematically possible, in the sense that it satisfies the appropriate equations and boundary conditions, but will not be observed because it is dynamically unstable, and still another régime where symmetric flow is not mathematically possible.

If the atmosphere is really analogous to the model experiments, the existence of eddies may be attributed to instability. A similar point of view was expressed by Eady[15], at the Centenary of the Royal Meteorological Society. Various studies of baroclinic instability have suggested that typical atmosphere zonal flow patterns are generally unstable.

The atmosphere thus falls into the unsymmetric régime because the particular combination of rotation and heating which characterizes the atmosphere is one of those which is incapable of maintaining large-scale symmetric convection, or stable symmetric flow. The existence of this combination of rotation and heating may be ascribed to chance; possibly a more nearly symmetric régime would prevail if the earth rotated more slowly.

The eddies in the atmosphere and the experiments are finite rather than infinitesimal, but it seems plausible that these eddies are maintained by the same processes which cause small eddies to grow when superposed upon an unstable flow. Likewise, any suppression of finite eddies may be due to the same processes which prevent small eddies from growing when superposed upon a stable flow.

If the zonal flow in the atmosphere is in general barotropically stable, the processes which tend to suppress the eddies convert their kinetic energy directly into kinetic energy of the zonal flow, since potential energy is not involved. If in addition the flow is baroclinically unstable, the maintenance of the eddies must result from a transfer of available potential energy, rather than kinetic energy, from the zonal circulation, and the kinetic energy of the eddies is obtained from the available potential energy which the eddies have acquired. We thus arrive at the picture of the energy cycle of the general circulation which we have already established from the observations.

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