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THE NATURE AND THEORY OF THE GENERAL CIRCULATION OF THE ATMOSPHERE

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I think the causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that Subject...

George Hadley, 1735.

The opening words of Hadley's classical paper afford an apt description of the state of the same subject today. Despite many excellent studies performed since Hadley's time no complete explanation of the general circulation of the atmosphere has been produced.

The physical laws upon which an explanation would have to be based are very complicated and not perfectly known. Many theoretical studies have therefore treated only an idealized atmosphere — usually one of uniform composition, enveloping an earth with a level homogeneous surface, and driven by a heat source not varying with time or longitude. A rigorous treatment of an idealized atmosphere sometimes affords a qualitatively correct although non-rigorous account of the real atmosphere.

The problem of explaining the circulation of even an idealized atmosphere is rendered difficult by the presence of advection — the displacement of the fields of motion and temperature by the field of motion itself. Because the motion is not uniform, different portions of the advected fields undergo different displacements, and the fields become distorted. The variety of patterns which the circulation may assume is therefore far greater than it would be if advection were not present, and the circulation shows little tendency to repeat its past history.

Mathematically the process of advection is manifested by the non-linearity of the governing equations. Because the general solution is non-periodic, it cannot be expressed explicitly with a finite number of symbols. Many theoretical studies have therefore aimed to determine only the characteristic properties or statistics of the general solution.

Closed systems of auxiliary equations whose unknowns are the desired statistics cannot be established, because the original equations are non-linear. The possibility of establishing closed systems consisting of equations and ordered inequalities has not been sufficiently explored.

The only presently feasible procedure for estimating the statistics consists of determining particular time-dependent solutions by numerical means, and evaluating the statistics of these solutions in the manner in which climatological statistics are evaluated from real weather data. The results often appear realistic, but the particular solutions are not always representative, and the procedure does not reveal the relative importance of the separate physical processes.

When averaged with respect to longitude, the advective processes appear as cross-latitude transports of angular momentum and energy. The atmosphere must carry sufficient amounts of these quantities poleward

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Editor's note: This article is a summary of the first *IMO Lecture*, delivered by Dr. Lorenz (Massachusetts Institute of Technology) to the Fifth WMO Congress, Geneva 1967.

across middle latitudes to balance the amounts which it receives from its environment in low latitudes and gives to its environment in higher latitudes. The required amounts may be carried by a meridional circulation — net equatorward flow at some levels accompanied by net poleward flow at others — or superposed large-scale eddies — cyclones and anticyclones, troughs and ridges. A direct meridional cell, with equatorward flow below and poleward flow aloft, would carry angular momentum and energy poleward.

Hadley explained the trade winds and prevailing westerlies by noting that heating should produce a direct meridional cell in each hemisphere. The equatorward current at low levels should be deflected by the earth's rotation to become the trade winds. The returning poleward current aloft should be deflected to become the upper-level westerlies, which upon sinking should become the surface westerlies. In its time Hadley's paper appeared to offer a satisfactory explanation.

Early nineteenth-century observations indicated that the surface westerlies drifted poleward rather than equatorward. James Thomson and William Ferrel introduced schemes in which shallow, frictionally-induced, indirect cells occurred in middle and higher latitudes, underneath the larger direct cells. Their explanations also appeared sufficient in their time.

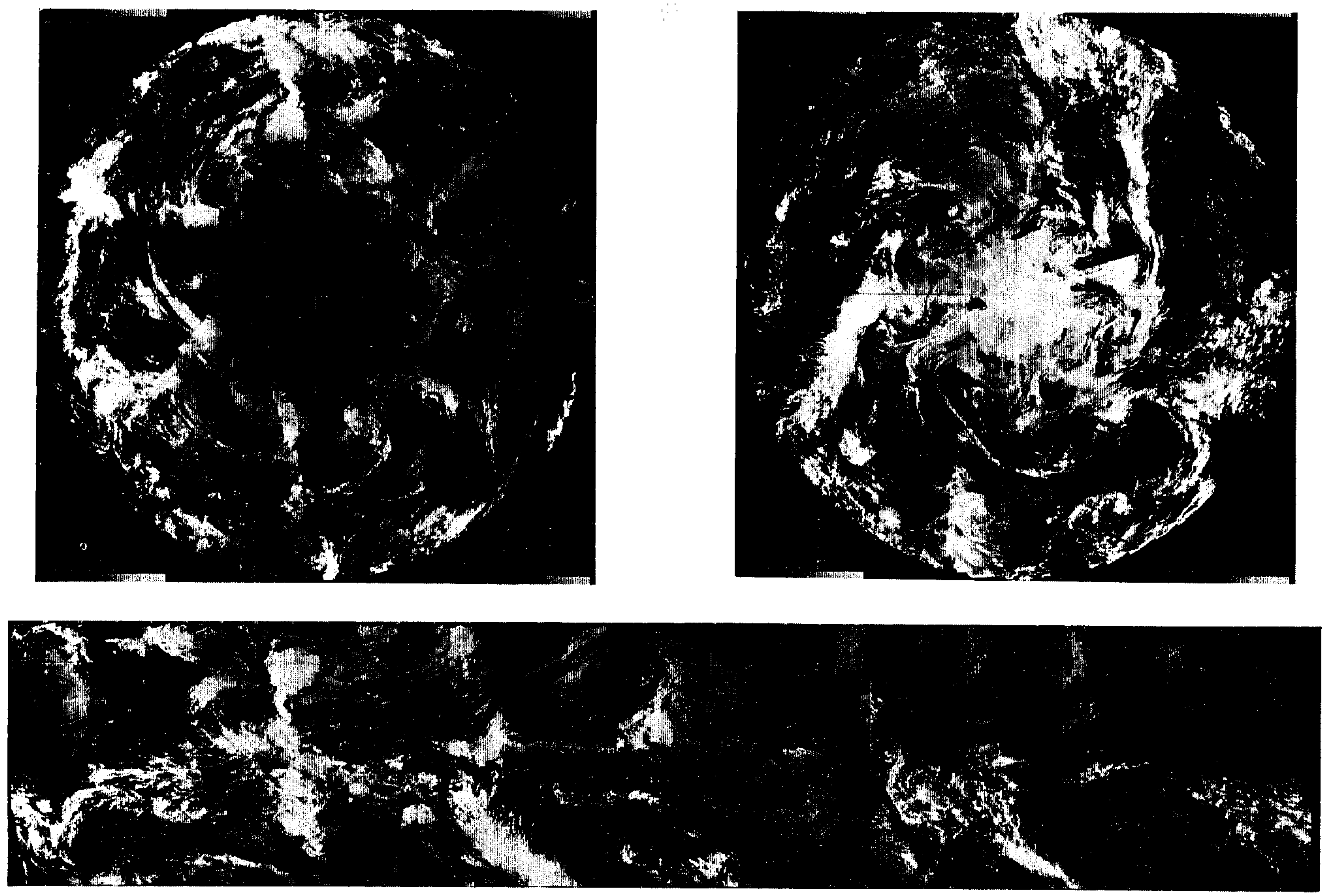
Late nineteenth-century observations of cloud motions, culminating in the international cloud observations instigated by the International Meteorological Organization, indicated that the supposed upper-level poleward currents across middle latitudes did not exist. No scheme of meridional cells consistent with the observations could be found which would transport the required angular momentum and energy. Ultimately the zonally-symmetric schemes of the circulation had to be abandoned.

Modern observations reveal that large-scale eddies exert a dominating influence upon the zonally-averaged circulation by transporting angular momentum and energy poleward across most latitudes. The transport of angular momentum by the eddies is concentrated near the tropopause, and it attains its maximum values near the thirtieth parallels. To complete the balance there must be direct meridional cells in low latitudes, stronger than Hadley's theory would have demanded, and indirect cells in middle latitudes. These cells must extend through the depth of the troposphere.

Since the meridional cells alone do not transport the proper amounts of angular momentum and energy to satisfy the balance requirements, the zonally-averaged circulation does not by itself satisfy the dynamic equations. The problem of obtaining pertinent solutions of the equations is therefore much more difficult than it had appeared to be when zonally symmetric solutions were considered sufficient. Any complete explanation of the zonally-averaged motion must include an explanation of the configuration of the eddies.

The eddies gain their energy from the zonally-averaged circulation in the form of available potential energy, by transporting energy toward latitudes of lower temperature. They supply kinetic energy to the zonally-averaged motion by transporting angular momentum toward latitudes of higher angular velocity. To deduce the latter result by treating the eddies as a form of turbulence, one would have to assume a negative coefficient of turbulent viscosity.

Circulations produced in rotating containers of fluid in the laboratory sometimes possess eddies similar in



Rectified cloud mosaics produced by computer from ESSA-3 satellite, 6 January 1967. Northern *(top left)* and southern hemispheres on polar stereographic projection; tropical belt *(below)* on Mercator's projection. Such mosaics will be of interest for studies of the general circulation structure to atmospheric eddies. It is thus implied that the physical factors responsible for the presence and structure of the eddies are those which are shared by the atmosphere and the laboratory models. Particular solutions of the dynamic equations obtained numerically also reveal eddies with the proper structure. It is thus implied that the most important physical processes have been incorporated into the equations as they are generally formulated.

For an idealized atmosphere certain specific features of the circulation can be readily explained. First, there must be a circulation, since a state of no motion would be incompatible with the poleward temperature gradient which radiative processes alone would demand. Next, since the kinetic energy of the circulation is dissipated by friction, the poleward temperature gradient must be somewhat less than that demanded by radiation alone, in order that available potential energy may be generated by heating. The poleward pressure gradient must then increase with altitude, in agreement with the hydrostatic equation. To balance the pressure gradients the westerly wind component must increase with elevation, in approximate agreement with the thermal wind relation, or else there must be a strong downward transfer of northward momentum across middle levels ; there appears to be no mechanism for maintaining the latter process. At low levels there must be easterlies at some latitudes and westerlies at others, or else no systematic easterlies and westerlies at all ; otherwise there would be a net frictional torque which would progressively alter the rotation of the earth.

One circulation fulfilling these requirements is Hadley's circulation, possibly with Thomson's or Ferrel's modifications. This circulation must possess a direct meridional cell to transport the required amount of energy poleward. This cell also transports angular momentum poleward, whence there must be easterly surface winds in low latitudes and westerlies in higher latitudes.

Hadley's circulation and any other zonally-symmetric circulations are not observed, because they are unstable with respect to small-amplitude wave-like disturbances of large scale. The observed circulation must therefore possess eddies. The transport of angular momentum by these eddies largely determines the distribution of surface easterlies and westerlies. The structure of the eddies constitutes one of the outstanding aspects of the general circulation not yet theoretically explained.

One approach to the problem is based upon classical turbulence theory. The eddies are assumed to transport angular momentum and energy toward latitudes of lower angular velocity and temperature. There is no physical basis for applying this theory to large-scale eddies, and in any case it yields incorrect results.

Another approach is based upon the theory of baroclinic stability. The large-amplitude eddies are assumed to be similar in shape to the small-amplitude eddies which would amplify most rapidly when superposed upon the existing zonally-averaged circulation. The results are more realistic than those given by classical turbulence theory, but they are not in complete agreement with observations, and the physical basis is somewhat uncertain.

The eddies appear to be less irregular than the turbulence approach would suggest, and less regular than the stability approach would suggest. Both approaches assume that the eddies acquire some sort of equilibrium configuration determined by the zonally-averaged circulation. It is likely that the eddies cannot be described in this manner, since, while attempting to reach any equilibrium configuration, they will produce a new zonally-averaged circulation which will in turn demand a new equilibrium configuration for the eddies.

It appears possible, that for an idealized atmosphere, some closed system of equations and ordered inequalities whose unknowns are statistics may be derived; this system might be solved rigorously for the upper and lower boundaries for the transport of angular momentum by the eddies across middle latitudes. From such a solution it may be possible to formulate a comprehensible qualitative argument, explaining why the eddies must transport angular momentum poleward, and hence why the trade winds and prevailing westerlies appear where they do.