Commentaries Concerning Research on the General Circulation

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Abstract

Several phases of research significant for the general circulation are reviewed briefly. The effect of rotation on convective regimes is discussed. An example is given showing that mean meridional circulations are not essential for the release of potential energy.

During the past several years the present writer has been conducting observational studies on an extensive scale with the aim of securing measures of various quantities chosen on the basis of their direct dynamic significance for the primary mechanism of the general circulation.[1] An outcome of central importance which emerges from this work is that the required meridional transports of angular momentum in the atmosphere are due primarily to horizontal eddy exchange processes, together with the closely allied concept that the kinetic energy of the mean zonal motions is maintained against friction to a large extent by a transference of kinetic energy from the large-scale horizontal eddy kinetic energy to these mean motions.

This action of the eddies is so marked and unambiguous that probably no amount of additional data, if properly brought to bear upon the question, would controvert it.[2] Furthermore, this link in the operation of the general circulation as depicted by the data is so dissimilar to the picture given by most classical schemes which ascribe the drive for the mean zonal motions to the Coriolis force on net meridional flow of air at individual levels, that no really successful manipulation of language or logic can identify them as being, after all, one and the same. We are thus confronted by a state of affairs which, although not completely unsuspected before, is relatively novel in character and hence intriguing—and in many ways puzzling. We must, however, be on the qui vive in our thinking in order to eliminate such difficulties as are merely apparent and not real, and free ourselves of incorrect prepossessions.

In order to show that this behavior of the atmosphere is not unique we may call attention to recent developments of paramount importance for the resolution of the general circulation problem, in the field of experimental hydrodynamics due principally to the original work of D. Fultz and R. Long at the University of Chicago. The particular experiments in question involve the generation of flow patterns in a rotating shallow cylindrical vessel of water resulting from differential heating, which under specified circumstances

[1] It would now appear that the long range planning originally involved in formulating this protracted program has already borne sufficient fruits not only to justify it, but also to suggest rather forcefully the desirability of placing such activities on a firmer footing than has hitherto been possible. Such steps have been advocated before by the writer elsewhere (see STARR 1951), on the basis of preliminary results.

[2] See Appendix.

assume forms similar with respect to a variety of detail to those comprising the atmospheric general circulation (see FULTZ 1952). Some of this work has recently been repeated by A. Faller at the Massachusetts Institute of Technology.

For the purposes of this discussion (and, it should be added, in this writer's opinion) the outstanding new concept made available through these experiments is that the otherwise simple and familiar regime of convective motions is profoundly altered as soon as the rate of rotation exceeds a definite value determined by external parameters such as the intensity of the differential heating. The more intense the heating, the higher becomes this critical rate of rotation. For slow rotation, below the limiting rate, the convection proceeds in an axially symmetric manner with zonal motions developing in much the same fashion as presupposed in the classic explanations of the general circulation. In this case the mean meridional circulations are quite apparent. For rotations higher than the critical one similarity to the atmosphere is obtained as to the following properties (among others): (a) The mean meridional circulations are no longer obvious except perhaps in the form of weak remnants as boundary layer phenomena. (b) Horizontal exchange processes appear to be dominant in the meridional transport of momentum and no doubt other properties as well (see STARR and LONG 1953). The eddies involved are again "waves in the westerlies" as in the atmosphere. (c) The motions appear to be quasi-geostrophic except in the boundary layers. (d) Some evidence of structures within the fluid having the characteristics of occluding cyclones with attendant frontal phenomena has been noted.

To the statement of these experimental findings one should add here a remark concerning some theoretical analyses suggested by them. The symmetrical one is of course the more tractable of the two regimes to study thus, and here the subject has received attention notably from T. V. DAVIES (1952). Still more recently, through the inclusion of the effects of heat advection, H. L. KUO (1953, 1954) has been able to state a necessary condition for the existence of an axially symmetric Hadley type convection in this so-called dishpan experiment. It turns out that a non-dimensional number P involving (among other parameters) the rate of rotation and the axis-to-rim density contrast, is the governing quantity which discriminates between the two regimes and assumes a critical value P_c at the turn-over point. The actual experiments seem to fit in with the theoretical value of P_c in a very satisfactory manner. Preliminary estimates of an analogous parameter for the atmosphere indicate the presence of unmistakable high rotation conditions.

To summarize the situation, it appears that the effect of rotation, if it be rapid enough, is to inhibit large scale convection as ordinarily conceived, and to substitute for it a process which produces the necessary radial transfer of heat and of certain other properties through the agency of quasi-horizontal eddy motions of which cyclones, anticyclones and their attendant upper troughs and ridges are the prime example.

In discussing these matters with other meteorologists the writer has noted frequent skepticism. These reactions seem to imply that any scheme which does not contain some form of the classic convective motions as a starting point is in a general sense too unnatural to be valid, although it is usually not easy to proceed further in order to discover wherein precisely the alleged difficulty lies. It turns out, however, that these attitudes spring mainly from a belief, whether articulate or not, that mean meridional circulations of the toroidal type are indispensable for the utilization of the potential energy inherent in the equator-to-pole temperature gradient in the atmosphere. It is to be sure first necessary to define terms more accurately, but speaking generally this claim is but a delusion, which in actuality the atmosphere circumvents without any real difficulty.

In order to exhibit the nature of the fallacy involved, it suffices to treat a very simple case in the dishpan. Let it be supposed that in the initial state there are two fluids of differing density separated by a vertical discontinuity concentric with the rim as shown in cross section in (a) of the figure and by the inner circle in (b) which is a view seen from the top. It is of course clear that if one of the fluids, say the inner one, is denser the system possesses a certain available potential energy, and the question now is whether some or perhaps all of it can be released without resorting to mean

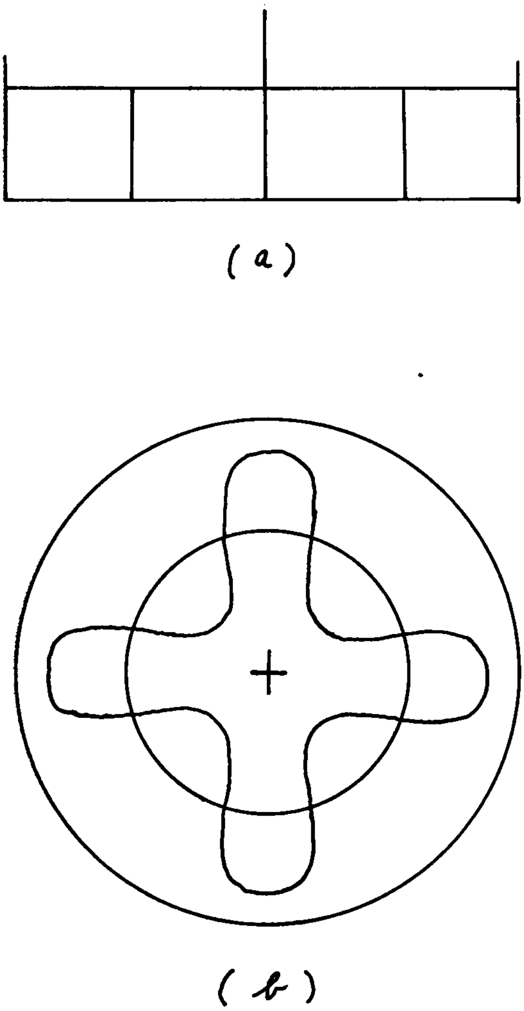

Fig. 1. Diagrams showing a possible rearrangement of two fluids in a cylindrical vessel, prior to the release of potential energy.

meridional circulations, or whether this is precluded through some topological constraint of the continuity principle or other kinematic consideration. It is here assumed that

$$\frac{d\varrho}{dt} = 0; \quad \nabla \cdot \vec{C} = 0; \quad [v] = 0$$

during the readjustment. In these relations ϱ is density, $\vec{C}$ is the vector velocity, v is the inward radial component of velocity, t is time and the square brackets denote zonal space averaging completely around the pan at a given radius and given depth so that the third relation constitutes the stipulation of no mean meridional circulations.

The answer is rather obvious. The total displacements may be divided into two stages so that in the first the vertical velocity w everywhere vanishes and $[v]$ is therefore identically zero because of the continuity requirement. The vertical discontinuity may therefore be deformed by purely two-dimensional motion into the lobed form shown. In the second stage vertical motions are supposed to take place in such a way as to release potential energy but still so as to make $[v]$ zero, say by having $v \equiv 0$, and allowing each lobe to diverge zonally near the bottom and converge zonally near the top (i.e., by having a downward eddy transport of mass).

With a little thought it becomes evident that the simplified model used here may be generalized to include much more complicated initial states involving continuous density distributions of various types, and that the separate stages of motion may be suitably combined. Also one could without difficulty modify the motions so as to liberate potential energy even in spite of a reverse mean meridional circulation, if the downward eddy transport of mass is vigorous enough.

The outlines of the analogous processes in the actual atmosphere are easily recognized on synoptic charts and are very basic meteorological phenomena, appealing as such even to a casual observer.[1] They are embodied in the large-scale outbreaks of cold and warm air so typical of weather conditions over a wide range of latitude. Viewed from the present standpoint these facts suggest anew the importance of such endeavors as those of Rossby (1949) and Phillips (1949) to study the mechanism for the release of potential energy by the sinking of cold air domes.

[1] We here make the tacit (but probably correct) assumption that the release of geopotential energy is necessary for the maintainance of the general circulation. Since the total geopotential energy of the atmosphere must on hydrostatic principles bear a fixed ratio to its total internal heat energy, and futhermore since the sum is maintained at a more or less fixed value when radiational and other effects are included, it becomes a philosophical problem of considerable complexity to ascertain whether the generation of kinetic energy takes place more directly from one of the forms of energy mentioned rather than the other.

Appendix

As pointed out by STARR (1953) the transfer of kinetic energy from the eddies to the mean zonal motions is a deep-seated process intense enough to generate in a short period of time an amount of such energy as is normally present—even according to measurements which are probably underestimates of its true potency. The inquiring reader may nevertheless propose that in spite of the fact that it is difficult to secure accurate measurements of the mean meridional circulations in the atmosphere due to their smallness, as an experiment a direct calculation should be made of their efficacy in generating mean zonal kinetic energy through the action of the Coriolis force, using the best data at hand. Formally this can be done with the aid of the compilations of actual wind statististics for the calender year of 1950 given by STARR and WHITE (1954) and used in the reference given above. However, as has been stated frequently by these authors, much is left to be desired in such use of the data, and the calculations made here can indeed be viewed as an experiment only.

The hemispheric wind statistics were compiled from daily data for 13°, 31°, 42°, 55° and 70° N latitude for levels from 1000 to 100 mb. The first consideration is that due most probably to a bias in the selection of the station network so as to favor unduly conditions either to the front of troughs on the one hand, or of ridges on the other, small net mean velocities were obtained across the several latitude walls. These, in order, were −22, −03, −17, +37 and +64 cm $\sec^{-1}$ (velocities taken positive northward). Only the last two are really serious in regard to magnitude and would imply a mean rising motion in the polar regions at practically all levels in the troposphere and into the stratosphere, if taken literally. In view of this situation, these mean values of the meridional velocities were subtracted out from the data at all latitudes in an effort to minimize spurious effects. All mean meridional circulations were taken to be zero at the equator.

The effect of the Coriolis forces associated with the mean meridional circulations in producing kinetic energy of mean zonal motions is an amount $\varrho f [\bar{u}] [\bar{v}]$ per unit volume (see, e.g., KUO 1951). Here ϱ is density, f the Coriolis parameter, u the eastward and v the northward component of wind velocity; brackets signify zonal averages and bars time averages. The (volume) integrals of this quantity by latitude belts and also for the whole northern hemisphere (up to 100 mb) are given in the table below in units of 10^{20} ergs per second.

No measures of statistical significance were calculated for these figures, although this could have been done, let us say by computing the daily results and then finding the standard error of the mean. It was not deemed worth the while to do this.

Although it is true that not much reliance can be placed upon the particular outcome here obtained, it should be carefully observed that there exists no valid reason which would necessarily exclude the possibility of such a small negative value of the integral for the hemisphere. The contribution of the energy transfer from the eddies is sufficiently large to allow for this (see STARR 1953 and ARAKAWA 1953). Also one may note that it is the (indirect) cell in middle latitudes which is most effective for the present problem, because an equally intense one at low latitudes is rendered much less potent due to the smallness of the Coriolis parameter, while nearer to the pole the length of latitude circles and hence the amount of air involved becomes small. A net destruction of kinetic energy of mean zonal motions by mean meridional circulations would imply as suggested by CHARNEY (1951), that these latter are merely secondary effects, or perhaps associated with surface friction as discussed by FLOHN (1953), for example.

It is doubtful whether the technique of subtracting out the over all mean velocities across latitude walls really eliminates all the unwholesome consequences of any appreciable bias in the sense of sampling of conditions to the east of troughs unduly, as probably was the case at 55° and 70° N. In the forward portions of troughs at high latitudes there usually is found an increase with elevation in the troposphere of the northward component of the wind. Mere subtraction of the over all mean velocity still leaves an abnormally large sampling of this vertical shear in the data, which then manifests itself as a spuriously strong direct mean meridional cell at a northerly location. The positive contributions shown in the table north of 55° N may owe their origin in part to such an artificially introduced circumstance.

In the computations made above, only the effect of the Coriolis term in generating kinetic energy of mean motions was evaluated. This term, however, occurs in combination with others which likewise represent means through which the mean meridional circulations can contribute to the generation of this kinetic energy. For example the term $[\varrho w] [u] \frac{\partial}{\partial z} [u]$ also enters the problem (see KUO 1951). Here w is the vertical component of velocity and z is height. This quantity could be evaluated from the data already used, although the work was not actually done. Since in the troposphere the term normally takes the algebraic sign of the vertical motion, and since this motion is apt to be downward in the latitudes of the strongest vertical shear in the westerlies, it is quite possible that the total effect is negative.

Many findings will no doubt be reported in the course of time relative to direct evidences of mean meridional circulations. What has been said here makes it evident that such claims must not only be scrutinized carefully as to their reliability, but also it is essential that their importance for maintaining the mean zonal motions be properly assessed from a sufficiently realistic viewpoint. For we have reached such a stage in the development of our subject, that the halcyon, free-wheeling days when investigators could propound mean meridional cells in a rough and ready manner to explain each feature of the mean zonal wind distribution, are irretrievably behind us.

Table 1. Volume integral up to the 100 mb level of quantity $\varrho \cdot f [\bar{u}] [\bar{v}]$ in 10^{20} erg $\sec^{-1}$.

Lat. Belt	0—13°	13—31°	31—42°	42—55°	55—70°	70—90°	Hemisphere
Integral	+ 0.01	−0.35	−3.55	−2.65	+ 2.69	+ 1.76	−2.09

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