Further Statistics Concerning the General Circulation

By VICTOR P. STARR

Massachusetts Institute of Technology, Cambridge, Massachusetts[1]

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During the past few years it has become increasingly clear that the newer outlook upon the fundamental processes of the general circulation continues to flourish and prosper. It bids fair to become the essential starting point for all rational discussion of the large motions of the atmosphere, as indeed it must if its principal ideas are correct. This stage has been reached not without much debate about logical matters, much effort to reinstate older schemes through secondary adjustments, and much examination of evidence. Also, any number of theoretical solutions, most of which lend support to the new views, have been advanced to illustrate the workings of the general circulation.

It likewise is worth our while to note that the trends of thought which have led us to what seems a more just view of this large subject do not find their entire application here, but have shown relevance also for smaller structures present in synoptic flow patterns. Here again consideration of the flow of momentum and the associated transfer of kinetic energy from one scale of motion to another seems to be a primary concept in the rational investigation of the behavior of synoptic systems. This is shown in a recent paper by SALTZMAN (1959). Another recent paper by KUO (1959) purports to show that, just as is the case for the circumpolar vortex, certain other large circulation systems may not release convectively their solenoidal energy. They presumably can be maintained in the atmosphere only through the action of still smaller eddies which do have associated baroclinic releases of energy in them. A general interpretation of all these developments has been given by STARR (1959).

Let us return to the larger problem, however. The writer (STARR, 1948) has long ago pointed out that the processes of gathering statistics concerning the new view of the general circulation would require much time and effort. We are still thus occupied, but since the results are quite gratifying, these labors are not so much of a burden as one might suppose judging merely from the amount of time and drudgery which is entailed. On the other hand, such work must be done, if we are to build solidly, because no other source of information can be equivalent to it (see STARR 1958 in this regard).

One activity which has its aim in this general direction is the work of SALTZMAN (1957, 1958). This consists of a plan to study the transfers of kinetic energy from the eddies to the mean zonal motions by use of the technique of spectral analysis, in order to examine the role played in this action by eddies corresponding to various wave numbers around the hemisphere. In addition, the process of convective kinetic energy release

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through vertical motions may also be brought within the ambit of the scheme. Aside from the partial results already presented earlier, new findings in this area, obtained from the analysis of a complete year of geostrophic data are now being reported by SALTZMAN and FLEISHER (1959). Still more extensive results are expected at a later date.

Since they serve as an interesting comparison to the Saltzman and Fleisher statistics, the writer wishes to make available the outcome of computations from actual wind data for an additional year, similar in an over-all fashion to those published several years ago (STARR, 1953) for the year 1950. The new findings are for the calendar year 1951—the same period as was used by SALTZMAN and FLEISHER.

The 1950 study concerned itself with the evaluation of an integral over the atmosphere in the northern hemisphere of the form

$$2\pi r^2 \int\int \varrho\,[u'v']\,coz^2\,\phi\,\frac{\partial}{\partial\phi}\left(\frac{[u]}{r\cos\Phi}\right)d\phi dz \quad (1)$$

u, v being the eastward and northward wind components, ϱ density, r earth's radius, Φ latitude, z elevation, the square brackets denoting averages along complete latitude circles, and the primes indicating deviations from such averages. Since the integrand contains, in proper form, the product of the eddy stress into the meridional shear of angular velocity of the mean flow, (1) gives the instantaneous rate of conversion of eddy kinetic energy into mean flow kinetic energy through the action of the horizontal wind. In almost all details the procedures used for the 1951 study are a duplication of those for the 1950 study (to which the reader is referred). The chief differences are due to the somewhat better quality and quantity of the 1951 data, so that it seemed desirable to make use of compilations for the 100- and 1,000-mb levels which were omitted previously. The following are the results.

(1) The expression above was evaluated on a daily basis. The average of these 365 values was $(5.8 \pm 1.0) \times 10^{20}$ erg sec^{-1}. All individual monthly values were positive. Since these calculations were made by levels and by days, this figure is comparable to that obtained in the previous study in paragraph (3) under »Critique and further computations», for the first half of 1950, namely 9.8×10^{20} erg sec^{-1}. The confidence limits are twice the standard error of the mean. The 70° N latitude data were included for 1951 in all studies.

(2) The use of a vertically-averaged momentum transport and a vertically-averaged shear (on a daily basis) in evaluating (1) resulted in a value of $(4.8 \pm 0.7) \times 10^{20}$ erg sec^{-1} for the year. All individual monthly values were again positive. This is comparable to the value $(4.5 \pm 1.0) \times 10^{20}$ erg sec^{-1} reported previously in paragraph (2) under "Critique, etc.", for the first half of 1950.

(3) When one resorts to computations based upon mean profiles for the year averaged vertically as well as with respect to time (comparable to those shown in Fig. 1 of the previous study), one gets the value of 4.6×10^{20} erg sec^{-1}. This is in good agreement with the value of 4.4×10^{20} erg sec^{-1} calculated for the entire year of 1950.

(4) Use of the 500-mb data alone for the momentum transport and shear, assuming these to be representative of the average for the atmosphere (on a daily basis) resulted in the quantity $(6.2 \pm 1.2) \times 10^{20}$ erg sec^{-1} for the year (all monthly values positive). A figure to be compared with this, based upon 500-mb geostrophic data, was obtained by SALTZMAN and FLEISHER, also for the year 1951. Their figure is $(3.8 \pm 1.2) \times 10^{20}$ erg sec^{-1} with all months positive. It is tempting to assume that the lower figure for the geostrophic calculations is mainly a result of a smoothing process in the drawing of maps of the contours from which gridpoint data were read.

It must not be lost sight of, that the present calculations are subject to all the strictures and qualifications enumerated in the discussion of the previous study. Such features as the probable underestimation of the total effects computed here, due to selectivity favoring more frequent observation of lighter winds at higher levels, is as true for the present data as for the previous compilations. Added to these, it should be borne in mind that individual years may vary greatly one from another in regard to the properties here studied. Shorter periods may of course show even more striking differences.

The data compiled for the year 1951 afforded an opportunity to repeat another calculation which the writer had the privilege to communicate some years ago in the pages of this journal, again using an assemblage of statistics for the calendar year 1950 (see STARR 1954). These two studies pertain to the measurement from actual wind data of the efficacy in the atmosphere of the classical mechanism for the maintenance of the kinetic energy of the mean zonal motions. As explained in the former paper such efforts are afflicted with great difficulties, but since a new set of extremely extensive and in many ways better observations offered another independent occasion to execute the computation, the resulting figures are given herewith.

For our present purpose it is needed to evaluate the effect of the mean meridional circulations in producing kinetic energy of the mean zonal motions through the action of Coriolis forces. This action is given by

$$\varrho f [\bar{u}] [\bar{v}[\qquad (2)$$

per unit volume of air. Here ϱ is density, f the Coriolis parameter, u the eastward and v the northward component of velocity, while the brackets denote zonal averages and bars time averages. The reader is directed to the former paper for added details. The volume integrals by latitude belts and for the hemisphere are given in the accompanying table together with a reproduction of the corresponding numbers for 1950. The figures for the hemisphere for both years show a net destruction of kinetic energy of mean zonal motions.

Since the kinetic energy stored in the mean meridional circulations themselves is always extremely small, and since the mean zonal motions are sensibly geostrophic, the negative value of the figures given above for the hemisphere possess the implication that the mean meridional circulations convert kinetic energy back into potential and internal. This has been commented upon, for example, by LORENZ (1955).

Excluding the figure quoted from Saltzman and Fleisher's study, the amount of data on which the results given for 1950 and 1951 are based is enormous. About a quarter million winds were processed—a task which has required the sustained efforts of a crew of skilled computers for several years. In view of the fact that much of the labor in this type of study consists in the tabulating of the initial observations, not much is gained through the use of electronic calculators, unless the input can be secured in a form already recorded on magnetic tape. Fortunately this is the case for the International Geophysical Year observations which are now being processed so as to obtain further information from data which no doubt are significantly better than either those for 1950 or 1951.

TABLE 1.

Volume integral for the atmosphere from 1 000 to 100 mb of the quantity $\varrho f [\bar{u}] [\bar{v}]$ in 10^{20} erg sec^{-1}.

Lat. Belt	0—13°	13—31°	31—42°	42—55°	55—70°	70—90°	Hemisphere
Int. 1950	+ 0.01	— 0.35	— 3.55	— 2.65	+ 2.69	+ 1.76	— 2.09
Int. 1951	+ 0.27	— 0.00	— 4.79	— 3.93	+ 3.61	+ 1.68	— 3.16

REFERENCES

KUO, H. L., 1959: Finite amplitude three-dimensional harmonic waves on the spherical earth. *J. Meteor.*, **16**, p. 524.

LORENZ, E. N., 1955: Available potential energy and the maintenance of the general circulation. *Tellus*, **7**, p. 157.

SALTZMAN, B., 1957: Equations governing the energetics of the large scales of atmospheric turbulence in the domain of wave number. *J. Meteor.*, **14**, p. 513.

— 1958: Some hemispheric spectral statistics. *J. Meteor.*, **15**, p. 259.

— 1959: On the maintenance of the large-scale quasi, permanent disturbances in the atmosphere. *Tellus*, **11**- pp. 425—431.

SALTZMAN, B., and FLEISHER, A., 1959: Hemispherci kinetic energy transfer spectrum (to be published in Tellus 1960).

STARR, V. P., 1948: An essay on the general circulation of the earth's atmosphere. *J. Meteor.* **5**, p. 39.

— 1953: Note concerning the nature of the large-scale eddies in the atmosphere. *Tellus*, **5**, p. 494.

— 1954: Commentaries concerning research on the general circulation. *Tellus*, **6**, p. 268.

— 1958: What constitutes our new outlook on the general circulation? *J. Met. Soc. of Japan*, **36**, p. 167.

— 1959: Trends of thought concerning meteorological research. *Geof. Pura e* **43**, p. 269.