Momentum and zonal kinetic energy balance of the atmosphere from five years of hemispheric data

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ABSTRACT

The angular momentum balance for the northern hemisphere is investigated from daily observations taken at about 800 sounding stations for a period of 5 years. A number of objective and other schemes of analysis are used in order to show possible differences arising from this source. The results are shown in many meridional cross sections through the atmosphere, for both the 60-month mean conditions and for four composite seasons of 15 months each. Profiles of vertical integrals of various quantities are also included. Some preliminary results concerning kinetic energy conversions are included, as an application of the momentum measurements. The results mainly agree with previous findings, although it is increasingly clear that vertical eddy flux processes contribute a vital part to the zonal kinetic energy balance through an added negative viscous effect. A new view of general circulation mechanics is threfore beginning to reveal itself.

Introduction

During the past several years the writers of this paper and their associates have been engaged in the perfecting and organizing of all more readily available data for a five-year period, suitable for the study of the general circulation over the northern hemisphere. This compilation has been named, "The MIT General Circulation Data Library". The period covered is from May 1, 1958 through April 30, 1963.

Although many uses have already been made of the Data Library for special purposes (see, e.g., Kung 1966*a*, 1966*b*, 1967; Starr, 1968; Newell *et al.*, 1970; Robinson, 1970), the present writers made a plan some time ago to investigate the properties and potentialities of the compilation through its application to the study of typical general circulation processes. Since assemblies of data of comparable scope and size have only to a small extent been previously brought to bear on the subject, it was anticipated, apparently correctly as it now appears, that much new and rather unfamiliar behavior of the atmosphere might be brought into view. Accordingly, it was decided that, at an early stage in the utilization of the data, much benefit would derive from its application to the calculation of those quantities and actions which are already most familiar in general circulation studies. In this way not only the advantages but also the limitations of the data might be be more readily assessed. Once this was done further novel calculations might be pursued later on a more trustworthy basis, where they seem feasible in the light of such an assessment.

In the present study the momentum flux across latitude circles and associated quantities are evaluated from the data. Also, preliminary studies of the kinetic energy of the zonally averaged zonal flow are presented. The theoretical derivation of the integrals and expressions used will not be repeated here, since the ordinary treatment is fairly standard at present. The reader is referred to Lorenz (1967), Starr (1968) and to Starr & Gaut (1969) for further comments on this topic.

The quantities analyzed are the following (dimensional and constant factors are omitted)

$[\bar{u}]$ — Zonal average of time-averaged zonal wind (1)

$[\bar{v}]$ — Zonal average of time-averaged meridional wind (2)

[1] On leave from the University of Lisbon.

ψ — Stream function for the meridional circulation (3)

$[\overline{u'v'}]\cos^2\phi$ — Transient eddy angular momentum transport (4)

$[\bar{u}^*\bar{v}^*]\cos^2\phi$ — Standing eddy angular momentum transport (5)

In the expressions above u and v are the eastward and northward wind velocity components, ψ is the stream function and ϕ is latitude. The bars indicate time averages over the entire five-year period or fraction thereof as indicated later. The primes indicate departures at a point fixed in space, from the time averages. The square brackets designate space averages over the length of a closed latitude circle, while the asterisks denote departures at a given longitude from the space average. See, e.g., Starr (1968) for a discussion of the expressions (1–4).

In addition to the five-year period treated in its entirety, four seasonal periods were also used in the calculations. Thus the data for the spring season were taken to include April, May and June for all 5 years taken together as a single assembly of 15 months. Analogous assemblies were used for summer, fall and winter. Aside from these composite seasons, no individual yearly or monthly subdivisions are discussed in this paper. Interannual variations and related questions pertaining to general circulation processes will be treated in future publications.

In the course of making the calculations numerous questions arose as to the methods to be followed. In many cases it is virtually impossible to choose what is best in the way of procedures, even though appreciable differences in the results arise. In other cases it is quite obvious that certain sets of results obtained through the use of superior techniques are themselves superior on that account. This is only natural in view of the complexities contained in the data. In order to give readers something of a feel for experimentation of this kind, six sets of results are given in this paper. These differ among themselves as to the amount of original and supplementary data used, statistical treatment, and mode of horizontal analysis of the hemispheric map distributions of various quantities. The first set of these results obtained through the use of what may be considered the simplest approach, has already been published by Starr (1968), but is included here for convenience of comparison with the further findings.

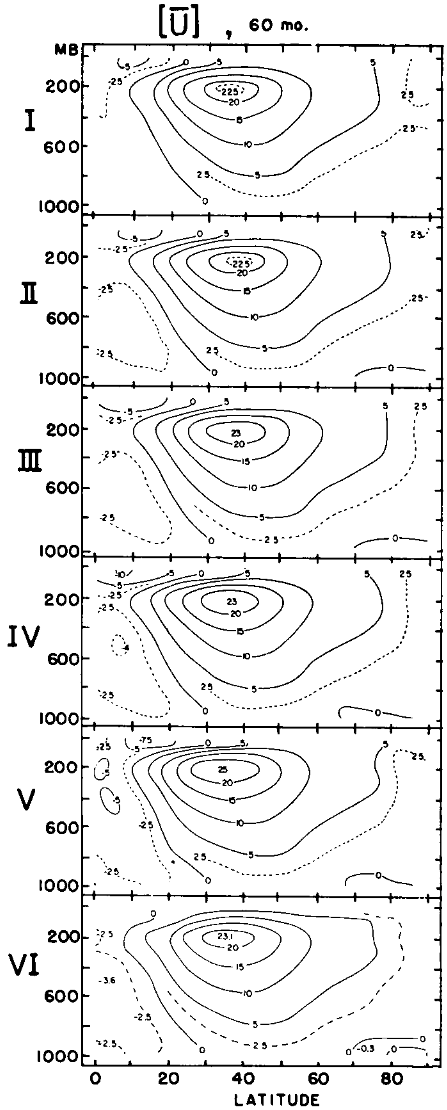

Fig. 1. Vertical meridional cross sections through the atmosphere showing the distribution of the mean zonal velocity $[\bar{u}]$, obtained by automatic computing from 5 years of daily data at 10 levels in the northern hemisphere for 60-month period and five versions of analysis techniques. The units are m sec^{-1} and the vertical coordinate is pressure in millibars. Version no. VI represents the results of a hand analysis.

The data library

The original basic portion of the MIT General Circulation Data Library consists of 120 magnetic tapes on which are recorded all readily avail-

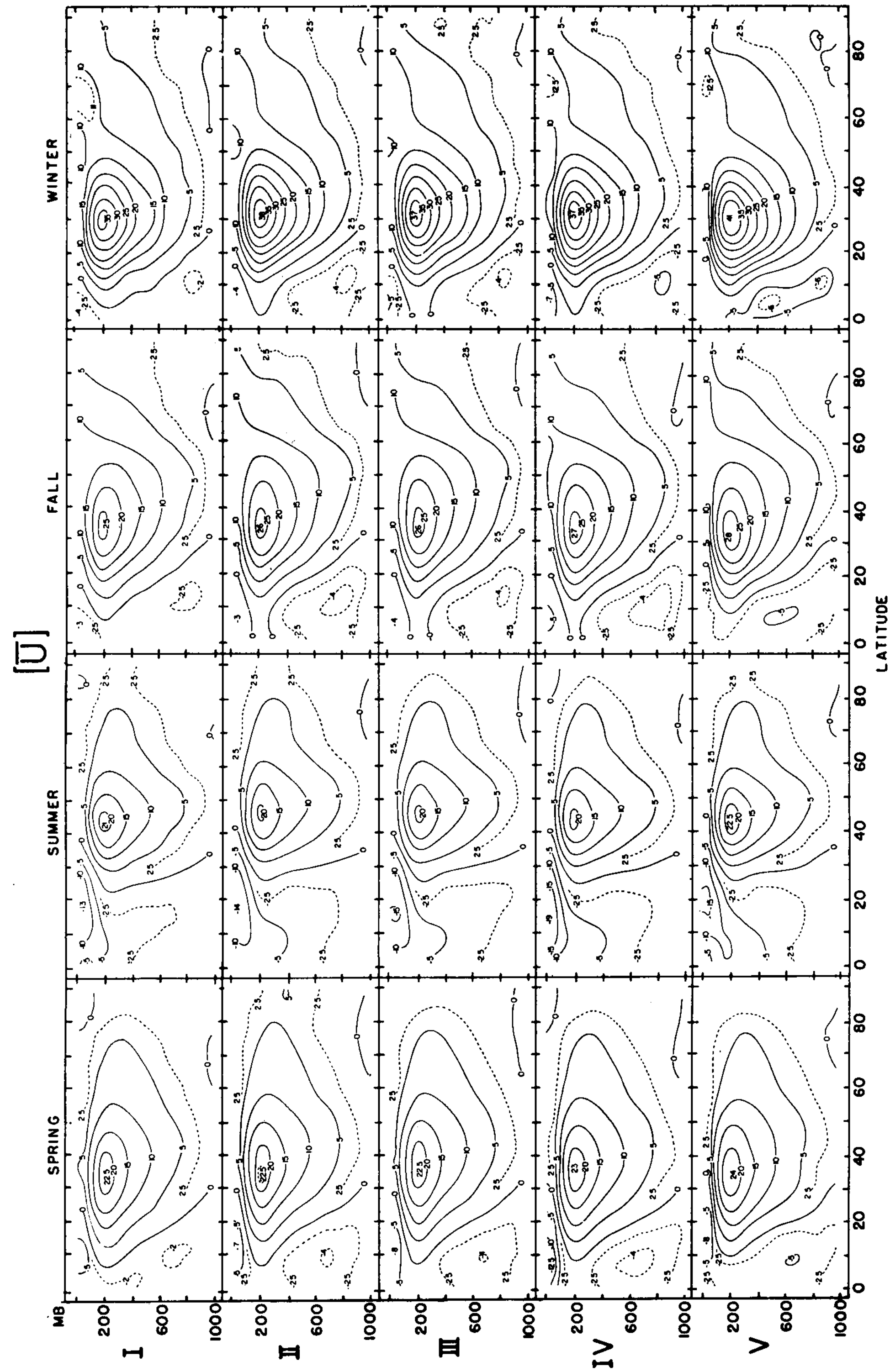

Fig. 1a. Similar to Fig. 1, but for four seasons.

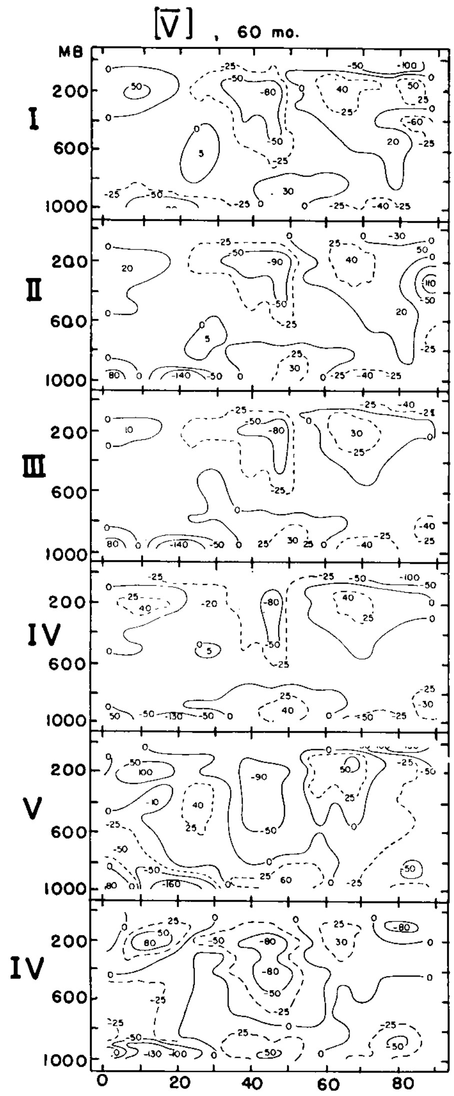

Fig. 2. Similar to Fig. 1, but for mean meridional velocity $[\bar{v}]$ in units of cm sec^{-1}. Version no. VI represents the results of a hand analsysis.

able meteorological observations for the northern hemisphere of geopotential, temperature, humidity and wind for 0000 GMT at a maximum of 27 pressure levels, during the five-year period mentioned earlier. The number of stations represented is 704. An effort was made to arrange the material for easy access in computing. One half of the tapes (the so-called station tapes) contain the data for all the stations in sequence according to an assigned numbering of the stations. Thus for station number one all the data values at level number one are given serially by days for the 5 years, whereafter the next level is listed, and so on until all the levels are complete. Station number two is then treated in the same way and so on.

The other half of the tapes (the so-called map tapes) list at the beginning, the reports from all the stations for level number one taken on day number one, followed by level number two, and so on. Day number two is listed similarly, and so on for all days in the five-year period.

For various reasons it was desirable to include in the library certain observations for 1200 GMT. Such material has been added more recently for about 200 stations located in the North American sector of the northern hemisphere. Also, for the present study, as explained more fully below, about 100 tropical stations were added (mostly for 0000 GMT) located as far south as 20° S in latitude. Thus far this tropical material has been added to the station tapes only, although it is planned to include it in the map tapes as well later. It is planned that eventually all available observations from the entire southern hemisphere will be added to both sets of tapes.

The data used were screened in order to eliminate, so far as possible, all erroneous and garbled reports. This was done by electronic means using absolute value checks, consistency checks and shear checks. Further refinements were made in this direction when residual incorrect data were otherwise detected during the performance of various computations.

Computations and analysis

For the present study the mean values $\bar{u}$ and $\bar{v}$ were computed separately at each station and level, as was also the temporal covariance $\overline{u'v'}$. This was done for each of the composite seasons and also for the 60-month period as a whole. Actually, all pertinent statistics were accumulated by months, then added together to obtain the results for the four 15-month seasons, as well as those for the 60 months. In much of the work the separation of the individual months was retained in the further analysis and computation, not so much to obtain monthly results but to spot more readily by inspection troubles with data and possible mistakes in the handling of it.

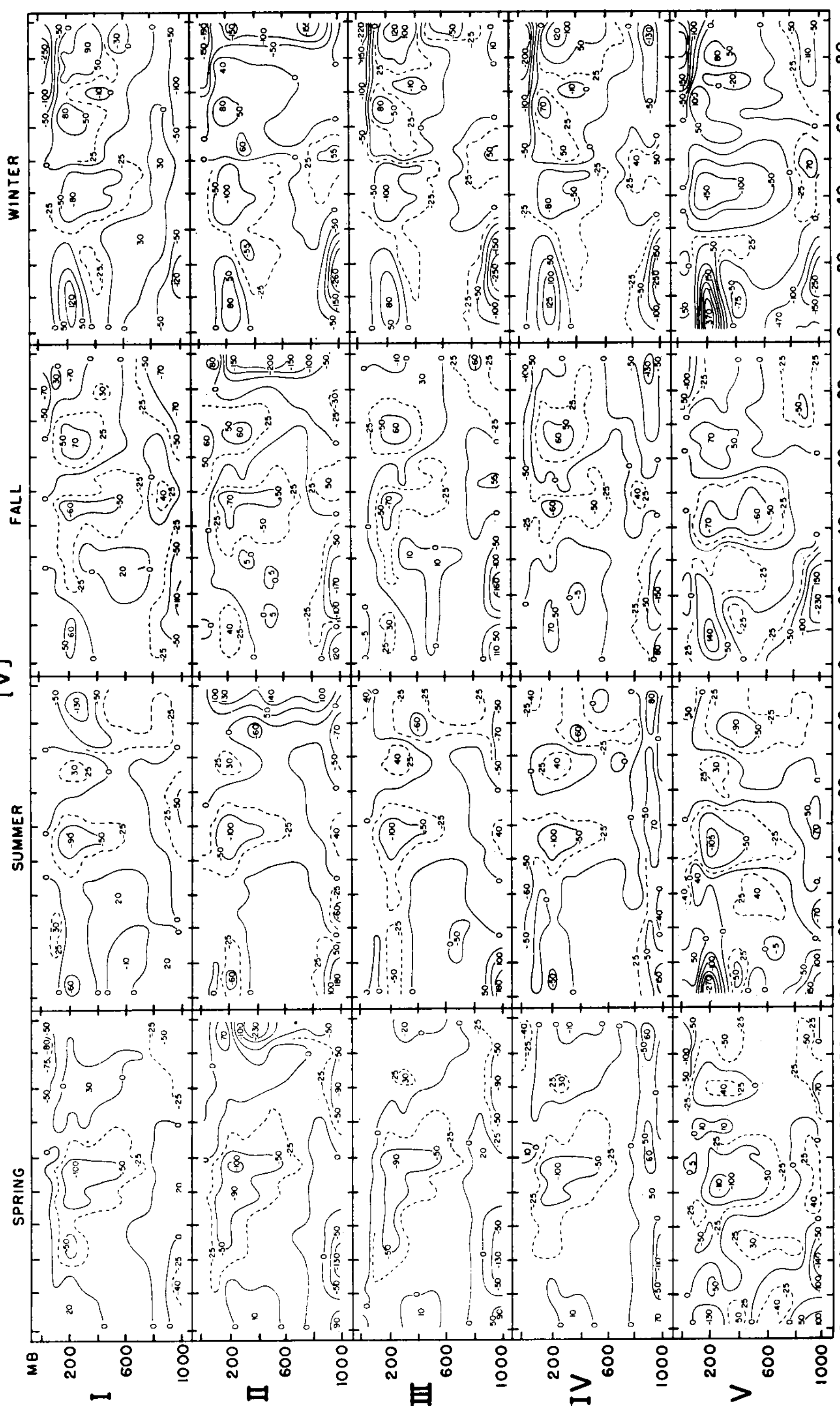

Fig. 2a. Similar to Fig. 2, but for four seasons.

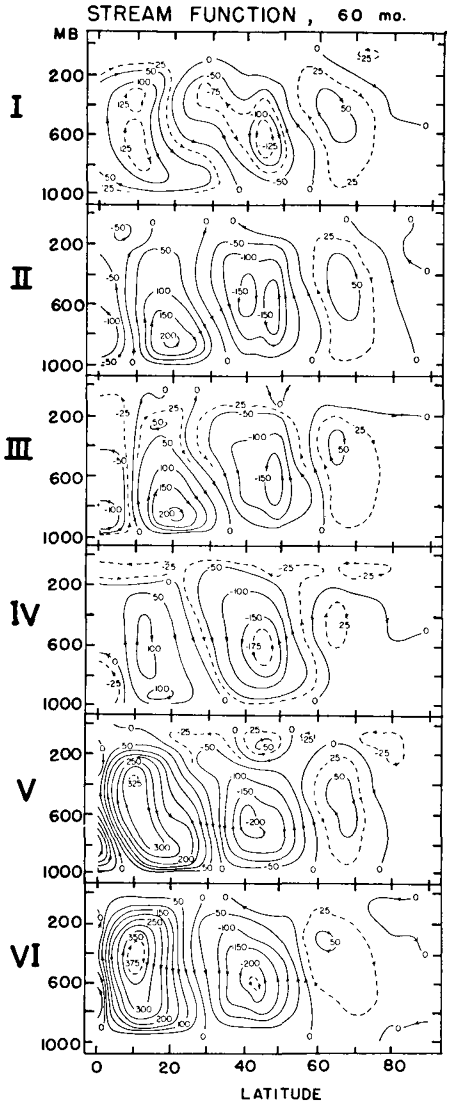

Fig. 3. Vertical meridional cross section through the atmosphere showing the distribution of streamlines for the mean meridional velocities $[\bar{v}]$ and the mean vertical velocities $[\bar{\omega}]$, the latter being determined by continuity considerations from the former. The numbers indicate values of the stream function fitted to the wind data. The units are 2×10^{11} g sec^{-1}. Version no. VI represents the results of a hand analysis.

In order to secure values of the several needed quantities at a regular 5° gridwork of latitude and longitude, the distributions represented by the station data were subjected to objective analysis by machine, except that one partial set of results was derived by hand analysis for purposes of comparison and to ensure an added visual inspection of the station data. As stated before, six sets of results were calculated in the order now to be briefly sketched.

I. Set number one was derived from the 704 stations in the basic portion of the library. As stated before, this is the set already presented by Starr (1968). The following ten pressure levels were used, 1000, 850, 700, 500, 400, 300, 200, 100, 70 and 50 mb. In order to exclude undue influence from stations having an excessively small fraction of the possible number of observations, a cut-off criterion was incorporated in the machine analysis program for the horizontal map at each of the levels. This criterion was set at 30 %, so that any station having less than this fraction of possible observations was discarded. The analysis used has been described by A. Thomasell & J. Welsh (1963). It incorporates an interpolation scheme and other simple devices. The initial guess used was that of the level immediately below (except at the 1000-mb level) in order to decrease the number of iterations required for a satisfactory fit. At 1000 mb the initial guess was a perfectly flat, featureless field.

II. In an effort to improve the analysis in the tropics about 50 additional stations on both sides of the equator down to about 20° S latitude were added to the original 704 in the second calculations. This included the addition of six stations over India. Also, in order to improve the analysis at 1000 mb, data from about 100 tropical pilot ballon stations were introduced. The cut-off criterion was lowered to 10 % applied to all stations at all levels to increase the amount of data used. The scheme for objective analysis was expanded to cover the enlarged area, but was retained essentially the same otherwise.

III. The third set of results was calculated for the purpose of examining the consequences of increasing the cut-off criterion, so as to make the acceptance of stations more stringent. Thus all else was retained identically the same as in the second set, but the cutoff was fixed at 30 % instead of 10 %.

IV. In the fourth set of calculations the number of added tropical and subtropical radiowind stations was increased to about 95 over the original 704 basic stations. The initial guess for the 1000-mb level was improved by utiliz-

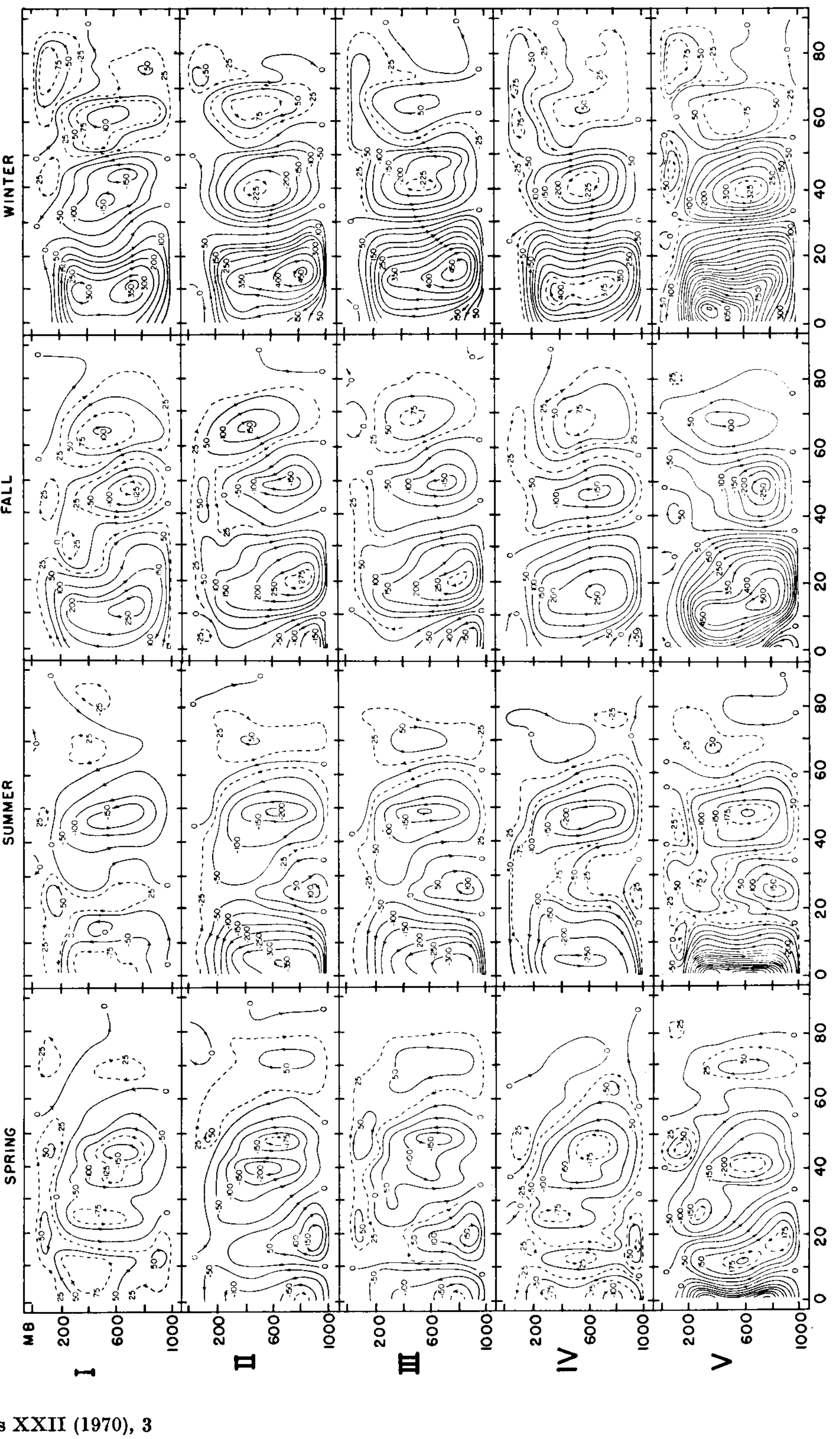

Fig. 3a. Similar to Fig. 3 but for four seasons.

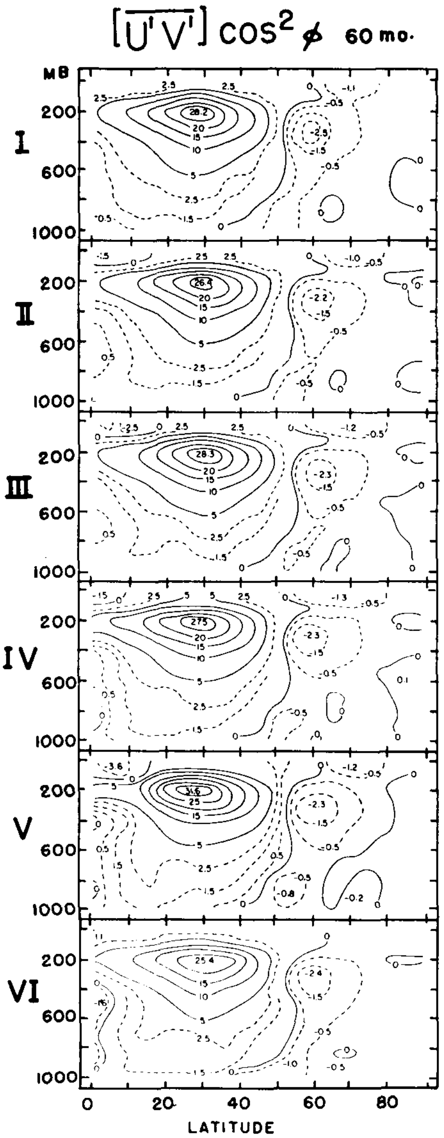

Fig. 4. Similar to Fig. 1, but for the northward angular-momentum transport by transient eddies. The values given are of $[\overline{u'v'}] \cos^2 \phi$, to be multiplied by $2\pi a^2$, a being the earth's radius. The units are $m^2\ sec^{-2}$. Version no. VI represents the results of a hand analysis.

ing an analysis given by Crutcher (1961). The scheme for the objective machine analysis was also improved in certain respects. The cut-off criterion used was 30%. All else was retained as in the third set, except that the 950-mb level was added in order to increase the vertical resolution near the surface.

V. The fifth set of results embodies an independent mode of performing the objective machine analysis of the horizontal maps at each level. The writers are indebted to Drs Abraham Oort and Eugene Rasmusson of the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton University for devising the scheme and testing it on our data. The observations used were essentially those of the fourth set, and the cut-off was 30%. The "first guess" in the analysis was a zonal average distribution.

VI. The sixth set of results was obtained by manual analysis of the maps according to customary synoptic practice. The data were those of the fourth set, but no fixed cut-off was used, the acceptance of station information being left to the discretion and judgment of the analyst. Gridpoint values were estimated visually from the analyzed maps. In the sixth set only the 60-month results were computed, because of the amount of labor involved in the actual drawing of the maps by hand.

In all six cases, once the gridpoint values were obtained, the five quantities defined in the introduction were computed through the use of a machine program involving finite difference procedures. In the case of the sixth set, the visually estimated values were punched on cards, transferred to tapes and fed into the same program. In some cases pilot hand computations of the final results were made from the gridpoint data as a further check on the machine procedures.

Results

It suits the purposes of convenience to present the bulk of the results graphically in the form of mean vertical meridional cross sections from equator to pole, and from the surface to 50 mb. The expressions (1)–(5) given in the introduction are displayed in Figs. 1–5 in the same order, for the total 60-month period. In each figure are given the cross sections for all six sets of results, in the order enumerated in the foregoing section. The results of the first five sets of computations for the four individual seasons are given in Figs. 1*a*–5*a*.

In order to aid the evaluation and interpretation of Figs. 1–5 and 1*a*–5*a*, a partial integration in space was carried out on the data represented by them. Thus, at each latitude the vertical average with respect to pressure for

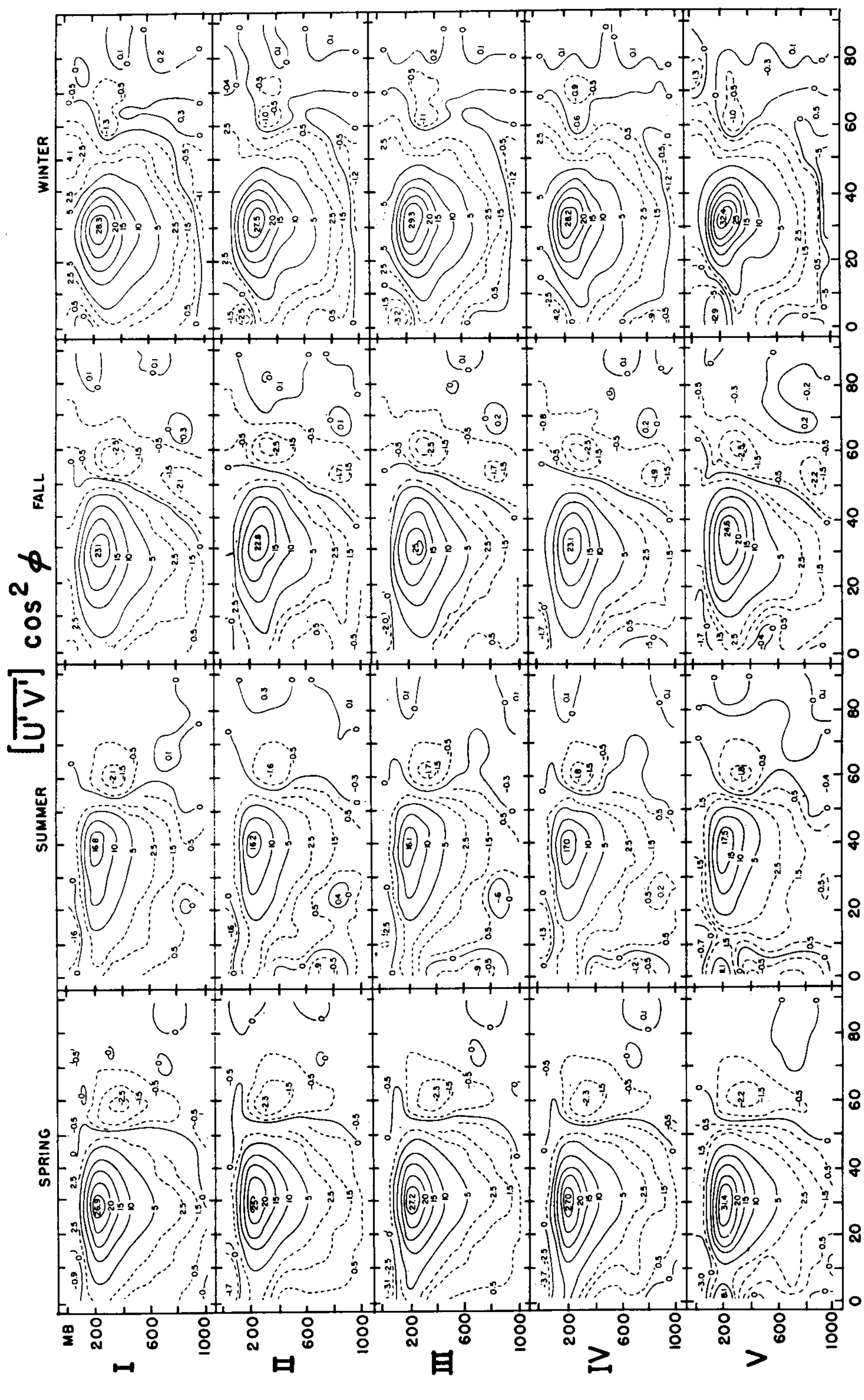

Fig. 4a. Similar to Fig. 4, but for four seasons.

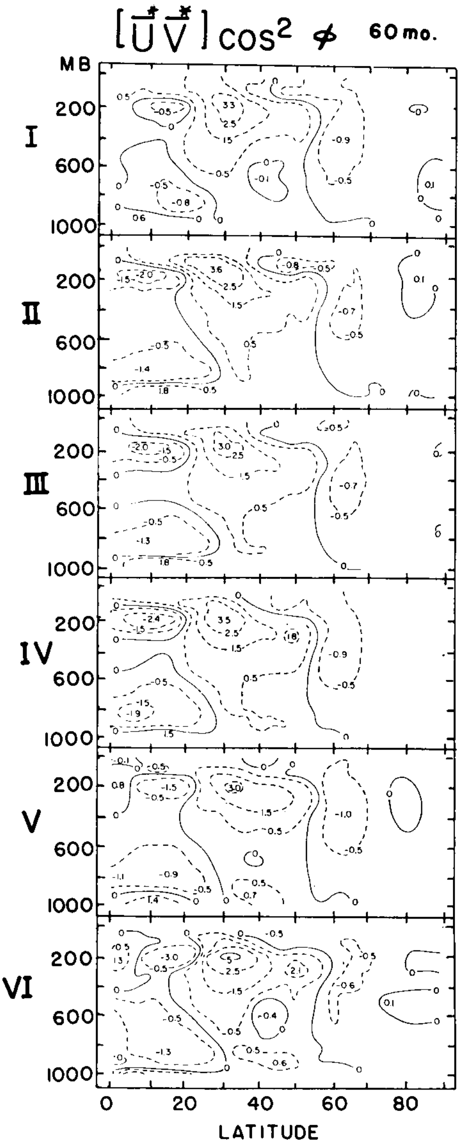

Fig. 5. Similar to Fig. 1, but for the northward angular-momentum transport by standing eddies. The values given are of $[\bar{u}^*\bar{v}^*]\cos^2\phi$, to be multiplied by $2\pi a^2$. The units are m² sec⁻². Version no. VI represents the results of a hand analysis.

essentially the whole extent of the atmosphere was computed. This resulted in 156 meridional profiles of these averages, extending in latitude from equator to pole. These profiles are reproduced in Figs. 6–7 and 6*a*–7*a* which include profiles of the vertically averaged mean angular momentum and mean angular velocity. Cross sections of these last two quantities are not shown.

One of the main purposes in computing the foregoing quantities is to evaluate some of the terms that are important for the study of the balance of the kinetic energy of zonal flow. These are the so-called conversion terms. Thus the following quantities were evaluated.

$$\underbrace{\iiint \overline{[u'v']}\cos^2\phi\frac{\partial}{a\partial\phi}\left\{\frac{[\bar{u}]}{a\cos\phi}\right\}a^3\,d\phi\,d\lambda\frac{dp}{g}}_{\text{Zonal kinetic energy generation by transient eddies}} \tag{6}$$

$$\underbrace{\iiint [\bar{u}^*\bar{v}^*]\cos^2\phi\frac{\partial}{a\partial\phi}\left\{\frac{[\bar{u}]}{a\cos\phi}\right\}a^3 d\phi\, d\lambda\frac{dp}{g}}_{\text{Zonal kinetic energy generation by standing eddies}} \tag{7}$$

$$\underbrace{\iiint 2\Omega[\bar{u}][\bar{v}]\sin\phi\cos\phi\, a^2 d\phi\, d\lambda\frac{dp}{g}}_{\text{Zonal kinetic energy generation by mean meridional circulation}} \tag{8}$$

In these expressions g is the acceleration of gravity, p is the pressure. The calculations were performed from equator to 82° N; for all longitudes, and for essentially the whole atmosphere in the vertical. The constant a is the mean radius of the earth.

These integrals were computed by entirely objective means using the various types of analysis described above, and the preliminary results so obtained for the hemisphere are presented in Tables 1 and 2. More definitive values as well as the corresponding vertical cross sections and profiles of the zonally and vertically averaged integrands will be published elsewhere in an article dealing more specifically with the balance of zonal kinetic energy.

Discussion

A. *General Comments.* In regard to the methods, materials and results outlined above, a number of general points may be noted. Among the more important of these are the following.

(1) The results are derived from a homogeneous set of checked data covering a fairly long period, and probably represent about as good

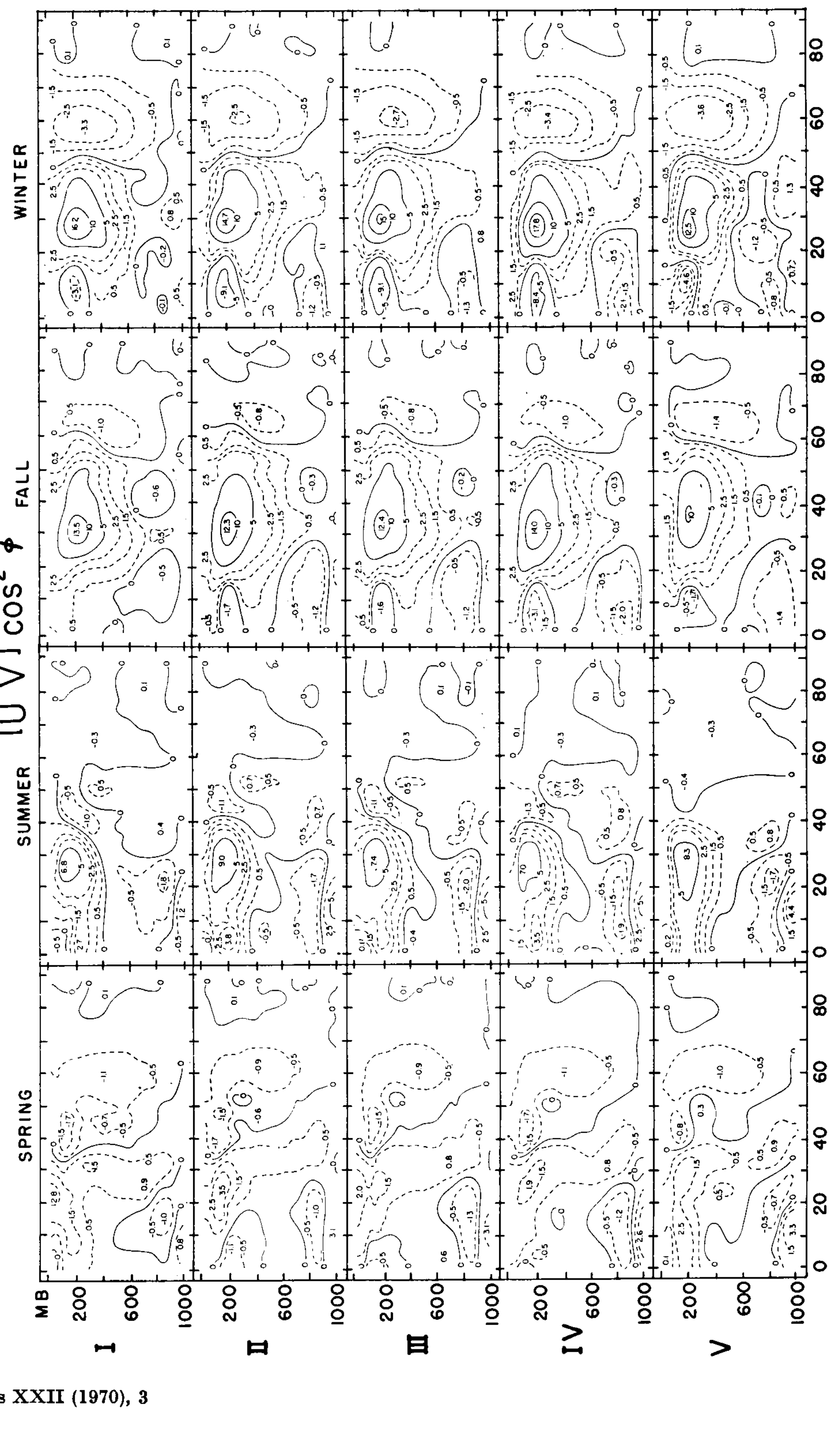

Fig. 5a. Similar to Fig. 5, but for four seasons.

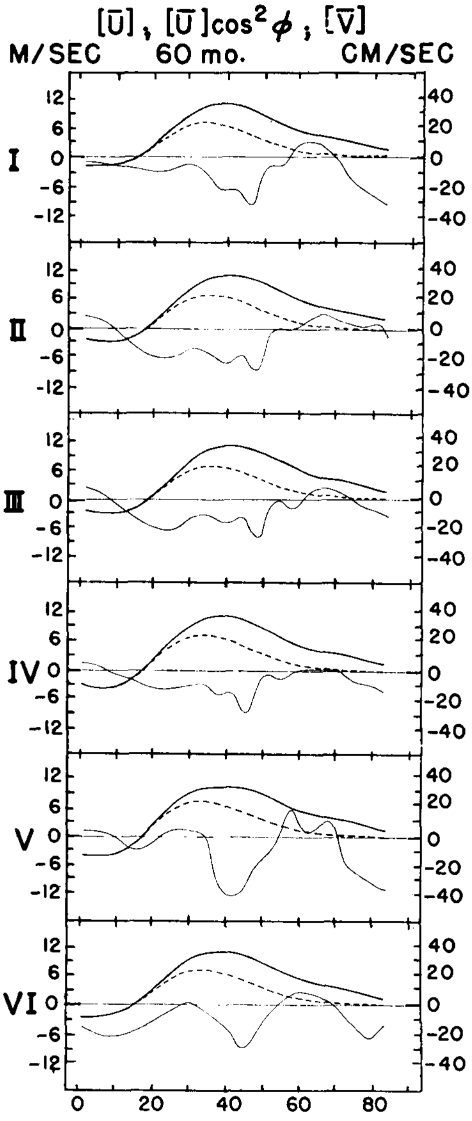

Fig. 6. Vertically averaged profiles of the mean zonal motion $[\bar{u}]$ (heavy full lines), of the mean relative angular momentum $[\bar{u}]\cos^2\phi$ (dashed lines) and of the mean meridional velocity $[\bar{v}]$ (thin full lines) obtained by automatic computing from 5 years of daily data at 10 levels in the northern hemisphere for 60-month period and five versions of analysis techniques. The units are m sec^{-1} for the vertically averaged mean zonal motion and cm sec^{-1} for the vertically averaged mean meridional velocity. The values of the vertically averaged relative mean angular momentum are to be multiplied by $2\pi a^2$. The units shown are m sec^{-1}. Version no. VI represents the results of a hand analysis.

a compilation as is currently available for the present purposes. Except as noted, the procedures are uniform and objective, the results down to the final cross sections, profiles and numerical tables being obtained by automatic computing, untouched (in a certain sense) by human hands. Thus the outcome, it is believed, allows the observations to speak and tell us something of the workings of the atmosphere.

(2) The use for purposes like the present ones, of nonhomogeneous data compilations and of nonuniform procedures, while perhaps justified under certain circumstances, introduces the danger of incongruities that could falsify the results rather completely in extreme cases, and render them inaccurate in others.

(3) The relatively simple quantities here evaluated, as has been mentioned, furnish something of a test as to the adequacy of the data and procedures for comparable other computations. Thus it is to be noted that in some cases of sensitive quantities even this compilation leaves much to be desired concerning portions of the results here given. Care must therefore be used in the determination of more novel, complex quantities not only from the present data, but even more especially from compilations less extensive as to the number of stations and period of record.

(4) An effort is made in the research reported here to calculate quantities as directly as possible from the data. In many instances it is possible to use various indirect methods of computing certain magnitudes. However, these processes often, and even perhaps usually, require the incorporation of assumptions which may seem reasonable but which have never been actually verified from data (such things as the nature of viscosity in the atmosphere, etc.). Direct measurements are therefore of prime interest, even though we are aware of the limitations of direct methods applied to currently available meteorological observations. In any event complications are compounded if we were to include in various computations both directly and indirectly determined quantities.

(5) In Fig. 8 there is shown the distribution of stations for which data were actually used at the 400-mb level. The inevitable question arises whether, in view of the preponderance of land stations, a fundamental bias is thereby introduced into the various results here reported. This question was investigated by H. Walker

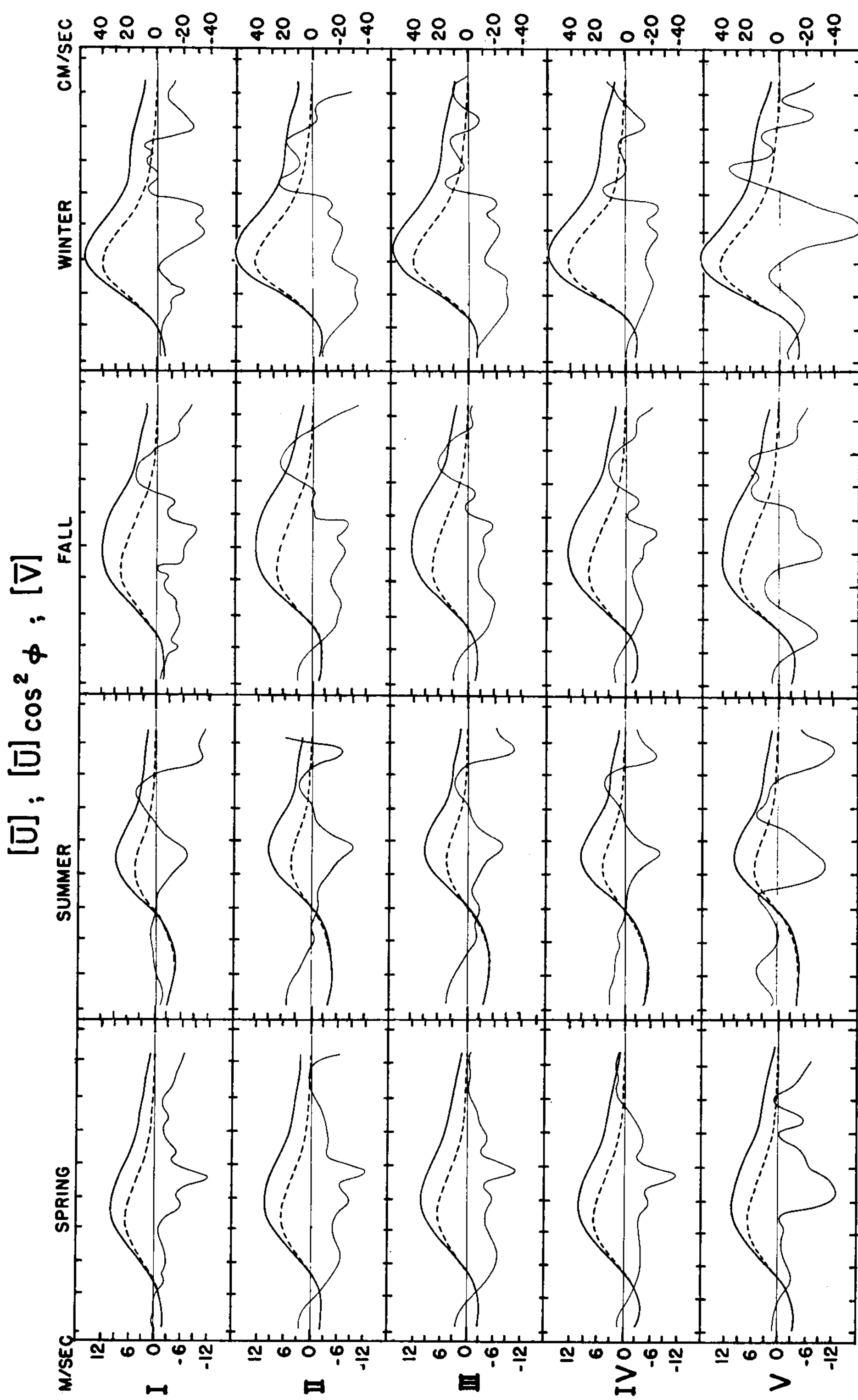

Fig. 6a. Similar to Fig. 6, but for four seasons.

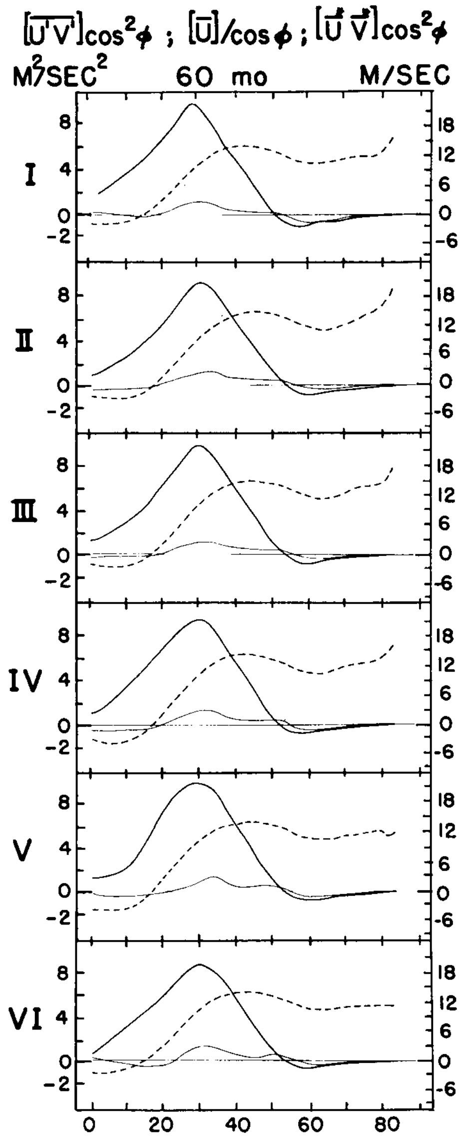

Fig. 7. Similar to Fig. 6 but for the relative mean angular velocity about the polar axis (dashed lines) and the northward transport of angular momentum by the transient eddies (heavy full lines) and by the standing eddies (thin smooth lines). The values of the angular velocity given are the integrals of $[\bar{u}]/\cos\phi$, to be divided by the earth's radius a. The units shown are m sec^{-1}. The values of the transports are to be multiplied by $2\pi a^2$. The units shown are m^2 sec^{-2}. Version no. VI represents the results of a hand analysis.

(1970), whose results are to be published elsewhere. The procedure used was to eliminate most of the land stations north of 30° N latitude so as to give a more nearly equal station density distribution over land and water. The new set of stations otherwise comparable to that of Fig. 8 is shown in Fig. 9. Various quantities were then computed by means of the identical machine programs used previously. Portions of the results are included in some of the discussions which follow.

(6) The observational materials in the form of data on tapes upon which the present study is based are available at cost to any users who may wish to secure them. The costs are only those of reproducing the tapes. It is planned that certain portions of the computed output prepared for the present study will be published in printout form at a later date.

B. *Cross sections and profiles.* The following more specific comments relate to the results presented in Figs. 1–7 and 1*a*–7*a*.

(7) Figs. 1 and 1*a* show the vertical meridional cross sections through the atmosphere of the mean zonal velocity of the wind for the various versions of analysis. Inspection of them reveals a good stability for all analyses, showing similarity and consistency. A well defined jet centered around 38° N in the upper troposphere is depicted in all the versions, with almost the same intensity. However, version V gives a value 10% higher than the others. The westerlies are predominant, while the easterlies in the low latitude are much less intense, appearing at surface south of 32° N.

There are some seasonal variations worth mentioning. The center of the westerly maximum progresses from 30° N in winter to 42° N in summer. At the surface the boundary between easterlies and westerlies advances from 28° N in the winter to 35° N in summer. Easterlies disappear with height most rapidly in winter and most slowly in summer. Version V shows higher values for all seasons in the jet, probably because of the nature of the "first guess" used in the objective analysis scheme.

(8) Figs. 2 and 2*a* show the vertical meridional cross sections of the directly measured mean meridional velocity $[\bar{v}]$, as given by the various versions of analysis. Contrary to the $[\bar{u}]$ analysis the present fields are not so well defined. Although the general orders of magnitude shown are correct the details vary considerably from analysis to analysis. Broadly speaking all the 60-month analyses reveal a cell structure as ex-

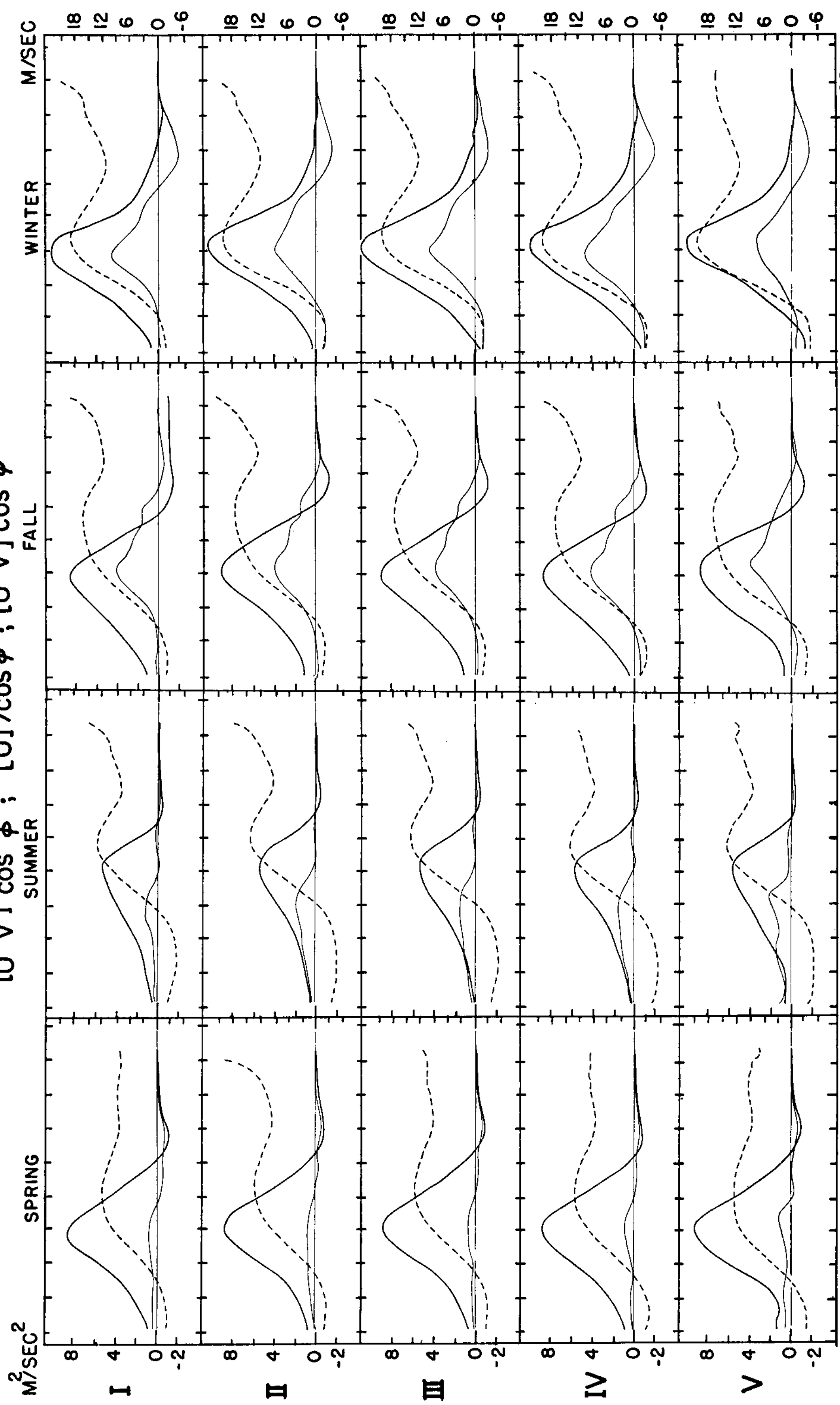

Fig. 7a. Similar to Fig. 7, but for four seasons.

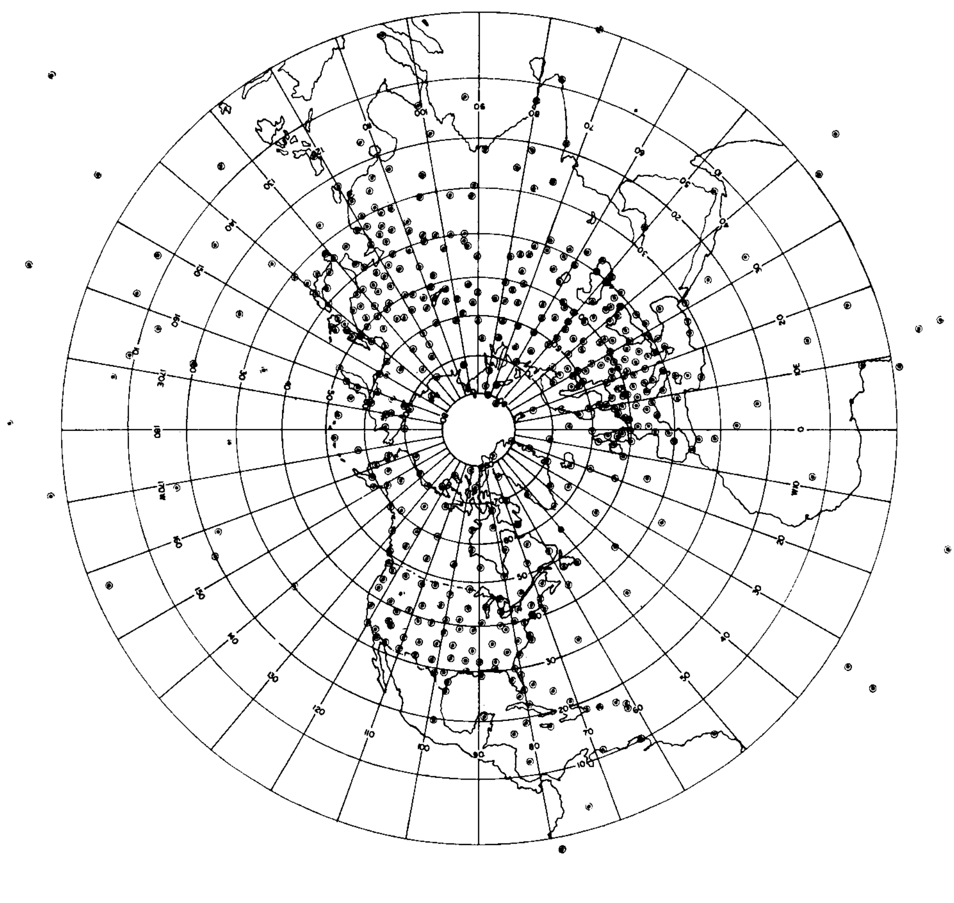

Fig. 8. Distribution of stations at 400 mb which had available at least 30 % of the total possible observations. This is the approximate distribution of stations used at all levels in version IV computations.

pected. In the equatorial region the northerlies appear near the surface and the southerlies predominate in the upper levels. In midlatitudes the directions are reversed. Near the polar regions northerlies show again at surface, whereas in upper levels the southerlies prevail. The anomalous values in polar regions as revealed in schemes I and II result from lack of sufficient data and other difficulties inherent in the neighborhood of the pole.

The results for the seasons show that qualitatively speaking the various versions of the analysis do not differ substantially. The extreme values are observed in the winter when the three cells are fully developed and reach maximum intensity. As seasons progress the northerlies penetrate further to the north reaching the highest latitude in summer. Scheme V shows consistently higher values than the remaining schemes, again most likely caused by the zonal average first guess.

The results illustrate the difficulty in determining the mean meridional motion by direct observations. The sensitivity of this quantity both to the observational sampling and to small changes in analysis schemes is evident. A meassure of the uncertainty involved in determining the $[\bar{v}]$ values is obtained when the vertical integration is performed. The integrated final values should become very close to zero, which is not strictly the case in any of the versions. This point will be discussed more later.

(9) Figs. 3 and 3*a* show the meridional cross sections through the atmosphere of the stream lines for the mean meridional mass transport. The streamlines were obtained by imposing the

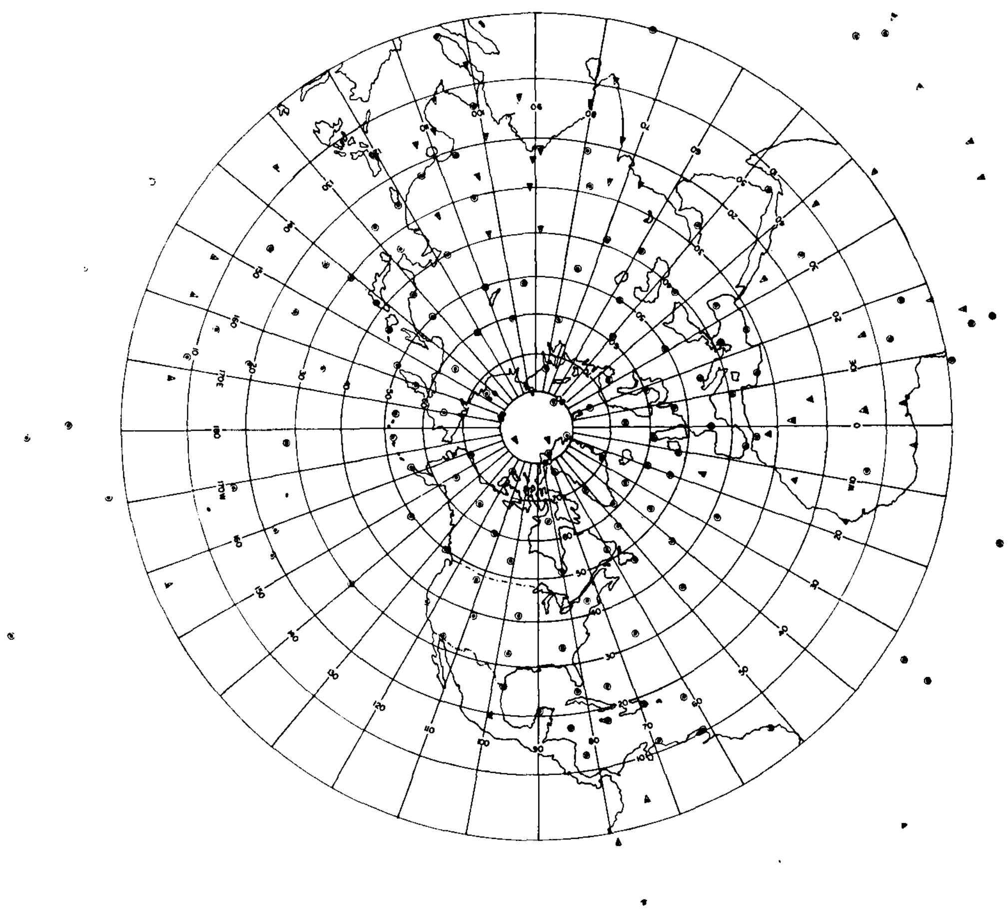

Fig. 9. Distribution of 206 stations which constitute a land-ocean minimum bias network. Those stations which have at least 30% data from 850 mb–100 mb inclusive are represented by circles. Some stations with less than 30% of the data at all levels were added to improve the analysis in the tropics. These stations are represented by triangles.

condition of zero mass divergence on the flow, which must be fulfilled by the atmopshere. The (mass) stream function ψ is implicitly defined using the equations

$$\frac{\partial \psi}{\partial p} = \frac{2\pi a}{g} \cos \phi \, [\bar{v}] \quad (9)$$

$$-\frac{\partial \psi}{\partial \phi} = \frac{2\pi a^2}{g} \cos \phi \, [\bar{\omega}] \quad (10)$$

where $\omega = dp/dt$ and g is the acceleration of gravity. The stream lines in Figs. 3 and 3*a* were derived by integrating equation (9). The general features of the $[\bar{\omega}]$ field can then be inferred using equation (10). The $[\bar{v}]$ values used in the determination of ψ were normalized so that the vertically integrated value of $[\bar{v}]$ equals zero, to ensure that, in the mean, no net flow of mass across latitude walls is implied. The normalization procedure at a given latitude was the simplest possible, namely by subtracting from the observed $[\bar{v}]$ values at each level the linear vertical average. It should be noted that equal gradients of ψ in either the p or ϕ directions give different values of $[\bar{v}]$ and $[\bar{\omega}]$ respectively depending upon the latitude because $[\bar{v}]$ and $[\bar{\omega}]$ are multiplied by $\cos \phi$. Figs. 3 and 3*a* contain essentially the same information as Figs. 2 and 2*a* but include also information concerning $[\bar{\omega}]$. All the pictures in Fig. 3 show a cellular structure with three cells well developed and a residual of the southern hemisphere Hadley cell in the northern equatorial region. Nevertheless the structure varies substantially in form and intensity from season to season. In fact the intensity of the cells *is largest in winter and smallest in summer*, although the intensities among the various analysis schemes differ considerably. During the year a migration accompanied by a cyclic variation of intensity is observed. The maximum northward penetration of the southern hemisphere Hadley cell occurs in summer, reaching 20° N latitude while the corresponding northern hemisphere Hadley cell weakens considerably. However, simultaneously with the intensification of this cell in the fall, which leads to a maximum observed in the winter, the northern hemisphere Hadley cell moves southward penetrating into the southern hemisphere. As a result of these fluctuations of the intensity and the north–south shifting from season to season the intensities of the mean cells for the 60-month period are substantially attenuated. This effect is clearly reflected in the low intensity of the Hadley cell as observed mainly in version IV, where the ratio of the intensities of the Hadley to the Ferrel cell is, in absolute value, slightly less than one. However, in versions V and VI the corresponding ratios are larger than one.

(10) Figs. 4 and 4*a* show the cross sections of the mean transport of *relative angular momentum by the action of the transient eddy motions*. The analyses for the 60-month period are very similar and fairly consistent in all the versions, except in version V which again shows higher values. Generally speaking, the maximum northward transport occurs around 30° N slightly south of the jet stream maximum. In middle latitude regions a center of southward transport of much lower intensity occurs north of the jet stream. The seasonal analysis as given in Fig. 4*a* shows that the transport is largest in winter with values almost as high occurring in spring. The lowest values occur in summer when the main center of poleward transport reaches the northernmost position. Centers of southward transport north of the jet stream are present in all cases. Slight southward transports occur across the equator in the middle and upper levels mainly during summer.

In comparing the various versions, we find that version V always gives the highest values of the maximum.

(11) Figs. 5 and 5*a* show the cross sections of the mean meridional transport of relative angular momentum by the standing eddy motions. The values obtained are smaller than the corresponding values for the transport of angular *momentum by the transient eddies*.

The results are fairly comparable in all the versions of the 60-month analyses. The values are positive (northward) in middle latitudes with a center of maximum transport at the 200-mb level slightly south of the jet stream. In the tropical and high latitude regions the transports are southward. In the tropics the transport is more intense and two centers of maximum develop, one in the low troposphere and another near the tropopause. The seasonal cross-sections show approximately the same configurations. The lowest values occur in spring and increase gradually to reach the largest values in the winter when the semi-permanent centers of action reach full development and highest intensity.

(12) Figs. 6 and 6*a* show the meridional distribution of the vertically averaged profiles of the mean zonal motion $[\bar{u}]$, of the mean relative angular momentum about the earth's axis $[\bar{u}]\cos^2\phi$, and of the mean meridional velocity $[\bar{v}]$. The results at each latitude were obtained by vertical integration of the corresponding cross sections through the atmosphere.

For the 60-month period the profile configurations of the mean zonal motion and mean relative angular momentum are very similar. The resulting values are positive north of about 18° N, with a maximum for the $[\bar{u}]$ values near 38° N and a maximum for the $[\bar{u}]\cos^2\phi$ displaced to the south. The profiles of the mean meridional motions $[\bar{v}]$ show a much more erratic distribution. From mass continuity considerations the vertical averages should be closer to zero than they are. The actual values should therefore be considered spurious. Hence they provide an indication of the reliability of the $[\bar{v}]$ values at various levels. It should be noted that the $[\bar{v}]$ profiles possess a negative minimum in middle latitudes in all instances.

The seasonal profiles of $[\bar{u}]$ and $[\bar{u}]\cos^2\phi$ are fairly consistent in all the versions. The intensities increase from summer when the maxima are found at higher latitudes, to the winter when the westerlies extend farther to the south. The seasonal profiles of $[\bar{v}]$ show basically the same shortcomings already mentioned for the 60-month period including the middle-latitude negative minimum.

Table 1. *Transformations of energy in the atmosphere expressed in units of 10^{20} ergs sec^{-1} for the atmosphere in the Northern Hemisphere.*

Because of nonlinear effects the figures for the total 60-month period are not equal to the means for the four individual seasons

	60-month	Spring	Summer	Fall	Winter
	Zonal kinetic energy generation by transient eddies				
I	+ 6.53	+ 5.24	+ 4.32	+ 6.72	+ 6.11
II	+ 6.30	+ 5.27	+ 4.66	+ 6.73	+ 5.99
III	+ 6.93	+ 4.73	+ 7.16	+ 6.27	+ 6.93
IV	+ 7.03	+ 5.60	+ 4.64	+ 6.98	+ 4.86
V	+ 7.16	+ 5.62	+ 4.69	+ 6.21	+ 2.55
VI	+ 5.70	—	—	—	—
	Zonal kinetic energy generation by standing eddies				
I	+ 0.46	+ 0.55	+ 0.79	+ 1.77	+ 1.05
II	+ 0.43	+ 0.52	+ 1.23	+ 2.03	+ 0.29
III	+ 0.40	+ 0.45	+ 1.09	+ 1.96	+ 0.63
IV	+ 0.35	+ 0.44	+ 1.05	+ 2.04	+ 1.21
V	+ 0.10	+ 0.60	+ 1.64	+ 1.11	+ 0.42
VI	+ 0.24	—	—	—	—

(13) Figs. 7 and 7*a* show the vertically averaged meridional profiles of the relative mean angular velocity about the earth's axis, $[\bar{u}]/\cos\phi$, and of the meridional transports of angular momentum by the action of the transient eddies $[\overline{u'v'}]\cos^2\phi$ and of the standing eddies $[\bar{u}^*\bar{v}^*]\cos^2\phi$.

The profiles for the 60-month period are very consistent in all the versions. The relative mean angular velocity showing small negative values in low latitudes where the easterlies predominate, increases rapidly between 18° N and 40° N to become almost constant or to decrease slightly to a local minimum about 60° N. The resulting value when integrated for the whole hemisphere is positive, indicating that on the average the atmosphere is rotating faster than the globe. The profiles of relative angular momentum transports by the transient eddies are very similar in all the schemes. The transport is northward up to 52° N, with a maximum near 30° N, and with very small values southward and in high latitudes. The standing eddies are much less efficient in transporting angular momentum. The corresponding values are positive in midlatitudes with a maximum in phase with the transient eddy maximum, but one order of magnitude smaller. These maxima occur slightly north of the latitude where the meridional gradient of the relative angular velocity reaches its highest value.

The seasonal profiles in the various versions have similar configurations and intensities of the same magnitude. The easterlies are evident in summer and almost disappear in winter when the westerlies are stronger. The efficiency of transient eddies in transporting relative angular momentum increases from summer to winter, while the standing eddies show the least activity, as mentioned before, in the spring. They reach extreme positive and negative values in winter when the poleward transport of relative angular momentum is almost 50% of the transport accomplished by the transient eddies.

C. *Preliminary results for energy transformation.* Some comments on the conversion terms that are relevant for the study of the balance of kinetic energy of zonal flow are now presented.

(14) Table 1 shows the results of the zonal kinetic energy generation by the transient and standing eddy motions for the 60-month period and for the four seasons, as evaluated from expresssions (6) and (7). In both cases the preliminary values given in version I (published previously by Starr (1968) are mostly confirmed in all the remaining versions. This shows that these quantities are fairly stable and the magnitudes of the results quite reliable. The values are always positive which implies a generation of kinetic energy of the mean zonal flow by the action of both the transient and the standing

Table 2. *Comparison of zonal kinetic energy transformations due to standing and transient eddy processes and those due to mean meridional circulations expressed in units of 10^{20} ergs sec^{-1} for the atmosphere in the Northern Hemisphere*

The values in parentheses are the directly measured estimates of the total eddy contribution

	60-month	Spring	Summer	Fall	Winter
I	−6.00 (+6.99)	−11.12 (+5.79)	−9.29 (+5.11)	+1.14 (+8.49)	−1.80 (+7.16)
II	−9.22 (+6.73)	−13.21 (+5.79)	−7.14 (+5.89)	−0.97 (+8.76)	−10.49 (+6.28)
III	−7.68 (+7.33)	−11.89 (+5.18)	−7.33 (+8.25)	−1.76 (+8.23)	−8.17 (+7.56)
IV	−5.19 (+7.38)	−12.70 (+6.04)	−6.51 (+5.69)	+3.15 (+9.02)	−4.47 (+6.07)
V	−4.31 (+7.26)	−10.23 (+6.22)	−8.34 (+6.33)	+5.51 (+7.32)	−4.36 (+2.97)
VI	−8.15 (+5.94)	—	—	—	—
VII	−3.87 (+7.13)	−10.90 (+5.95)	−1.97 (+6.18)	+2.67 (+8.90)	−3.73 (+5.40)
VIII	−2.23 (+7.88)	−7.68 (+6.73)	−6.92 (+6.96)	+7.53 (+7.86)	−0.42 (+2.72)

eddies. However, the inspection of the results shows immediately that the transient eddy motions are much more efficient in generating kinetic energy of zonal flow than the standing eddies, as expected.

The 60-month values are very consistent for both the transient and the standing eddy generations and are a little higher than previously found corresponding values (Starr, 1959). The low value shown in version VI for the transient generation results from the lower estimate of relative angular momentum transport, as shown in Fig. 7. Similarly, the low value given in version V for the 60-month standing eddy generation term is associated to the slightly smaller values of the angular momentum transport by the standing eddies, perhaps as a result of the "first guess" introduced in the analysis scheme, as mentioned before.

The seasonal values in all the versions are very similar. Their general nature seems plausible. The largest generation takes place in the Fall and the smallest in Summer for the transient eddies and in Fall and Spring respectively for the standing eddies, which is reflected in an acceleration of the general circulation processes in the Fall and a slowing down in the Spring and the Summer.

On the whole it seems reasonable to regard the results of version IV as perhaps more typical than the others for most purposes.

(15) In order to compare the three terms that enter into the balance of the kinetic energy of the mean zonal flow, it was found convenient to present another table. Thus, Table 2 shows the conversions due to standing and transient eddy processes combined, and those due to mean meridional circulations evaluated directly from expression (8). The values of the conversion integrals computed from observed values of $[\bar{u}]$ and $[\bar{v}]$ are given without parentheses. Besides the values corresponding to versions I–VI, Table 2 includes two more sets of results shown in rows VII and VIII. These were obtained, respectively from the Walker experiment and from an independent objective analysis scheme devised by Drs A. Oort and E. Rasmusson of GFDL, involving a weighted normalization scheme for the $[\bar{v}]$ values.

The values of the zonal kinetic energy generation by mean meridional circulations for the 60-month period are negative in all the versions, which implies an average destruction of kinetic energy of the zonal flow. These values show a strong variation from version to version in sharp contrast with the quasi-uniformity of the corresponding total eddy conversion terms.

In some cases the zonal kinetic energy generated by the standing and transient eddies would not be sufficient to overcome the action of the mean meridional circulation.

The fluctuations of the $[\bar{u}]$ $[\bar{v}]$ cos ϕ sin ϕ conversion integrals are clearly associated with the previously mentioned difficulty in measuring properly the $[\bar{v}]$ values upon which the integrals depend. Due to the weighting factor sin ϕ cos ϕ the value of the transformation integral is determined to a large extent by the middle latitude reverse cell. Since in these latitudes the equatorward flow occurs in the upper troposphere where the strongest mean zonal westerly winds are found the resulting values for the conversion integrals are negative. The contributions of thermally direct meridional circulations, which are present in the mean condition to the north and to the south, are small and too weak to overshadow the predominance of the reverse middle cell.

The seasonal values of integral (8) in versions I through VIII are negative in spring, summer and winter. The largest negative values are found in spring. In this season and in summer the implied destruction of zonal kinetic energy is greater than the generation by the transient and standing eddies combined. In fall the corresponding values are mostly positive which would lead to an increase of the kinetic energy of the mean zonal flow reinforcing the already strong generation accomplished by the eddies.

Emerging new view of general circulation mechanics

The prime questions posed by the five-year results pertain in the first place to the reality of the large negative contribution of the meridional circulations to the zonal kinetic energy balance, especially during the spring season. Fall is an exception when the opposite difficulty may be present. The second question is, how a balance is achieved, if the values are indeed real. In what follows we shall use the version IV results, considering them to be the most typical, as given in Table 2, although the situation in its general outlines was already indicated by version I and discussed in a preliminary fashion by Starr (1968).

One view, which we might abandon only with considerable reluctance when forced to do so, is to say that the meridional circulations have even now not been measured properly, due to various bias effects. One such possible source of bias was investigated by Walker (1970), as stated, with somewhat negative results. Another, might be an adverse effect of more severe weather conditions ahead of upper troughs in middle latitudes, leading to a smaller likelihood of securing measurements of winds with a poleward component at higher levels. This possibility is being investigated. Still other sources of bias might be conceived. On the other hand, the situation depicted in Table 2 may be roughly correct, and other methods of securing a proper balance of zonal kinetic energy must be examined.

The subject may be introduced by saying that it is an unwaranted assumption that the three terms considered above should be expected to balance. Rather, we must consider essentially the entire zonal kinetic energy equation, without making a priori assumptions as to which terms are important and which are not, allowing the data to speak in this regard. The results of such a more complete treatment, following Starr, Peixoto & Sims (1970), cannot be repeated here in detail. Nevertheless, certain important points may be mentioned in a general fashion. Among these are the following.

(*a*) Evaluation of eleven principal terms of the zonal kinetic energy equation, including frictional and mountain torque contributions, shows that a balance is indeed obtained, both for the 60 months and seasonally, so that the residuals (all positive) are reduced to less than 0.5×10^{20} erg sec^{-1} except in winter, where an as yet unlocated error is suspected. (The use of Walker's data reduces the winter residual to about 0.3×10^{20} erg sec^{-1}.)

(*b*) The method used does not require any specific theory of friction, the effects of which are lumped together with other eddy momentum flux processes. More precisely, no separation as to scale of motions is made.

(*c*) Vertical processes are obtained from horizontal ones through continuity considerations applied to mass and absolute angular momentum.

(*d*) Given the horizontal eddy momentum flux distribution and that of the mean zonal flow, the method provides a means for testing any scheme of proposed mean meridional motions for compatibility. Thus if a scheme for these motions known to be incorrect is used, the

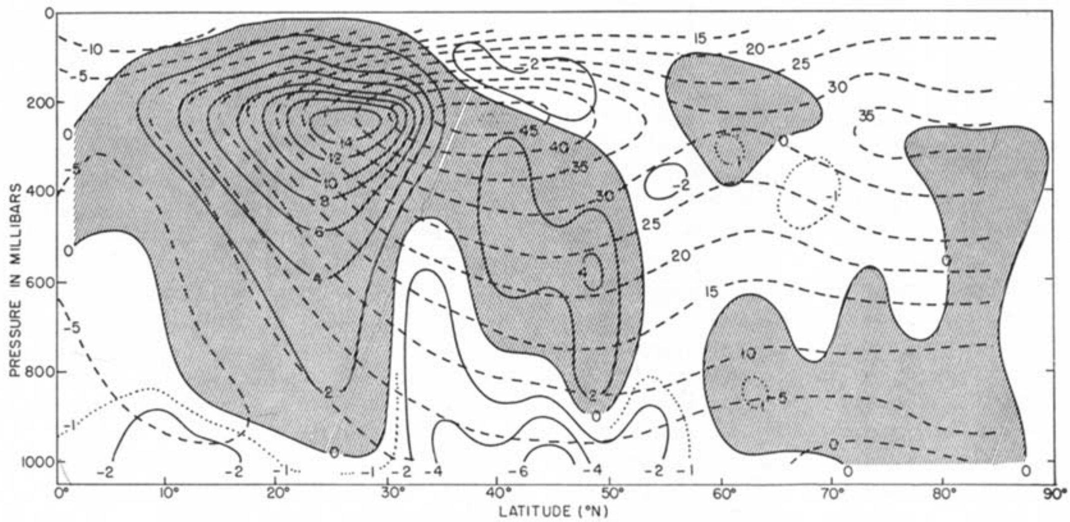

Fig. 10. Vertical meridional cross section through the atmosphere showing the integrand of the generation integral for zonal kinetic energy (full lines), similar to integral (6) in text, but including vertical eddy effects and friction in addition to the traditional horizontal eddy actions. The units are 10^6 cm^2 sec^{-1}. The dashed curves are the contours of zonally averaged zonal angular velocity $[\bar{u}]/a \cos \phi$. The units are 10^{-7} sec^{-1}. The quantities shown are for the 60-month period. (The full lines represent, in the notation of Starr, Peixoto & Sims 1970, the integrand of $\{3'\} + \{3''\} + \{6' + 6'' + 6'''\}$.)

residuals immediately blow up to large values, generally speaking. By-and-large, the smallest residuals are obtained by using the directly measured values of $[\bar{v}]$ normalized by removing the linear vertical means.

(*e*) The equatorial boundary integrals proper to the equation used, are all quite negligible for all five periods.

(*f*) The most important result pertains to the importance of vertical upward transports of angular momentum by the combination of standing plus transient eddies plus friction, against the gradients of angular velocity. Thus, over much of the hemisphere in the longterm mean condition (and still more so during spring) there exists in the vertical a negative viscous eddy action, even when the genuine frictional effects are included. Apparently in the long term mean for the hemisphere the negative viscous action of the large vertical eddies, generates almost enough mean zonal kinetic energy to offset frictional losses (and during spring it generates much more). Except for fall, large negative meridional circulation integrals are then needed in order to offset the additional positive generation by the negative viscous action of the horizontal standing and transient eddies.

(*g*) Portions of what has just been said are illustrated by the vertical meridional cross section for the 60-month mean condition shown in Fig. 10. The full lines represent the integrand of an expression for the eddy generation of zonal kinetic energy on the plan of (6), but including also vertical and frictional processes of momentum transport, and combining all transient and standing effects. The dashed lines show the distribution of mean angular velocity relative to the earth. Regions of positive value of the generation integrand imply a net transport (friction included) of angular momentum across the isolines of angular velocity toward regions of higher rotation. The strong secondary positive center at about 50° N in the troposphere may be the result of condensation processes which induce strong vertical eddy motions of a proper kind. The hemispheric value of the transformation integral from total eddy plus friction to zonal kinetic energy is $+6.4 \times 10^{20}$ erc sec^{-1}, as computed from this section.

(*h*) The remaining terms in the energy equation are small for the long term mean condition, save for the mountain torque term which acts negatively, like ground friction for the hemisphere as a whole, being -0.5×10^{20} erg sec^{-1}.

(*i*) The action of ground friction is automatically included in the cross section. Its influence apparently is evident in the predominantly negative values of the integrand at low levels, with a nodal point at about 30° N as should be expected. The very small positive values near the surface at high latitudes may not be real.

(*j*) There exists a relatively small leakage of mean zonal kinetic energy from the atmosphere into the oceans. This should be represented as a bottom boundary integral involving the motion of the sea surface. Such a term was not evaluated. However, the fact that the residuals obtained are positive leaves some energy available for such action.

(*k*) Observationally, the state of affairs described was to some degree indicated by P. A. Gilman (1964), who endeavored to determine the algebraic sign of the vertical eddy viscosity in the atmosphere from the early compilation of general circulation statistics by H. Buch (1954) for the northern hemisphere, and from that of G. O. P. Obasi (1963) for the southern hemisphere. His results are mainly in agreement with what has been stated. He also recommended the use of the five-year data for the purpose, when available. The possible importance of vertical processes to help achieve a balance was indicated by Starr (1968) in discussing the version I results then available.

From the point of view of numerical solutions, Smagorinsky, Manabe & Holloway (1965) presented results for a nine-level model which are in fair agreement with what has been said. Presumably the absence of the condensation effects in the solution prevented the appearance of the secondary positive maximum of generation at 50° N shown in Fig. 10.

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БАЛАНС КОЛИЧЕСТВА ДВИЖЕНИЯ И КИНЕТИЧЕСКОЙ ЭНЕРГИИ В СЕВЕРНОМ ПОЛУШАРИИ ПО ДАННЫМ ЗА ПЯТЬ ЛЕТ

Исследуется баланс момента количества движения в северном полушарии по ежедневным наблюдениям на 800 зондирующих станциях для пятилетнего периода. Используется как объективный анализ, так и другие схемы анализа, чтобы обнаружить возможные различия, возникающие из этого источника. Результаты показаны на меридиональных разрезах как для средних за 60 месяцев условий, так и для четырех отдельных сезонов по 15 месяцев в каждом. Приводятся также профили вертикальных средних значений различных величин. Излагаются предварительные результаты, касающиеся преобразований кинетической энергии, которые следуют из измерений количества движения. Результаты в основном согласуются с предыдущими работами, хотя теперь стало яснее, что процессы вертикального турбулентного обмена вносят ощутимый вклад в баланс зональной кинетической энергии посредством дополнительного эффекта отрицательной вязкости. Это приводит к новой точке зрения на механику общей циркуляции.