Vertical transport of mean zonal kinetic energy from five years of hemispheric data

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ABSTRACT

Vertical transports of the kinetic energy of the mean zonal flow across arbitrary horizontal surfaces which span the northern hemisphere are evaluated. The vertical processes involved are not directly measured but rather are obtained from observed horizontal motions through use of continuity requirements. It is found that vertical eddies can accomplish significant transports through horizontal boundary stress actions. A noteworthy feature is the downward eddy transport into the surface boundary layer.

Introduction

Sims (1970) has recently made use of observational data to evaluate the vertical boundary terms of the symmetric formulation of the zonal kinetic energy balance equation. This equation, presented in the space domain by Starr & Gaut (1969), also contains horizontal boundary terms which represent real physical transports of zonal kinetic energy across the free upper boundary of a polar cap region bounded below by the earth's surface. It is the evaluation of these vertical transport processes with which the present study is concerned.

Since it is our intent here to make use of hemispheric data which is taken over an interval of time, what we really require is a formulation of the symmetric equation in the *time and* space domain, rather than in just the space domain as given by Starr & Gaut (1969). Such a formulation may be easily obtained if one proceeds in a manner similar to that used by Starr & Gaut, and hence the details will not be presented here. In vector form, our desired symmetric integral equation for the balance of the kinetic energy of the zonally averaged zonal flow may be written as

$$\int_\tau \varrho[\bar{u}]\overline{\frac{\partial u}{\partial t}}\,d\tau = \int_\tau \varrho\bar{M}\bar{\mathbf{v}}\cdot\nabla\frac{[\bar{u}]}{R\cos\phi}\,d\tau + \int_\tau \varrho\overline{M'\mathbf{v}'}\cdot\nabla\frac{[\bar{u}]}{R\cos\phi}\,d\tau + \int_\tau [\bar{u}]\bar{F}\,d\tau - \int_s \frac{[\bar{u}]}{R\cos\phi}\varrho\bar{M}\bar{\mathbf{v}}_n\,dS - \int_s \frac{[\bar{u}]}{R\cos\phi}\varrho(\overline{M'\mathbf{v}'})_n\,dS \qquad (1)$$

The notation used in (1) is standard. The volume τ is taken to be a northern hemispheric polar cap region which is bounded by the earth's surface (assumed to be smooth) below, by a free horizontal boundary above, and by a free vertical latitude wall to the south. Thus the volume element $d\tau$ equals $R^2\cos\phi\,dR\,d\lambda\,d\phi$, where the spherical polar coordinates (R, λ, ϕ), which refer respectively to radius, longitude, and latitude, are assumed to rotate about the polar axis at the earth's angular velocity Ω. The symbol dS refers to an element of the free bounding surface, and the subscript n denotes a component normal to this surface. The vector velocity $\mathbf{v}$ has components (u, v, w) which, in order, are the linear eastward, northward, and upward relative particle velocities. Further, ϱ is density, F is the frictional force per unit volume, and $M = R^2\cos^2\phi(\Omega + (u/R\cos\phi))$ is the absolute angular momentum per unit mass of fluid about the polar axis. Finally, overbars indicate linear averages with respect to time t, while primes signify departures from these temporal averages. Square brackets indicate averages with respect to the length of complete latitude circles, while asterisks will be used to signify departures from such zonal means.

Because (1) is so similar in nature to equation (12) of Starr & Gaut (1969), a lengthy discussion of its properties is unnecesary here. The essential feature of the symmetric scheme given in vector form by (1) lies in its boundary terms for, excepting direct advective processes, they together represent all the physical means by which zonal kinetic energy may be transported across a free boundary. (Note by the way that (1) also implies positive generations of zonal kinetic energy in the volume can be accomplished only through countergradient transports of angular momentum.) As indicated earlier, Sims (1970) has evaluated with data those components of the boundary flux in (1) which represent meridional transports of zonal kinetic energy across vertical boundaries; it is our purpose here to consider those components of the boundary flux which measure the vertical transports across horizontal boundaries. It is worthwhile to point out however that given the present state of meteorological knowledge, our treatment of vertical transport processes in the atmosphere cannot be so straightforward or precise a matter as was Sims' consideration of horizontal transport processes. In particular, since it is not yet possible to measure directly vertical velocities in the atmosphere, it becomes necessary to infer mean and eddy vertical transports of zonal kinetic energy from continuity restrictions. In our case, these vertical transports are obtained through use of the observed horizontal wind fields in the equations for conservation of mass and conservation of angular momentum in a mean meridional plane (see Starr, Peixoto & Sims, 1970, for details). Such an indirect technique has its shortcomings of course, but nevertheless it is felt that methods such as we employ here can still provide some significant insight into the nature of atmospheric energy processes. We might, for example, cite in advance our finding that important transports of zonal kinetic energy into the surface boundary layer can be accomplished through stresses associated with vertical eddies.

The data used in this study are the same as those employed by Sims and represent the daily upper-wind observations from 799 available stations, mostly over the northern hemisphere, taken during the period from May 1, 1958 through April 30, 1963. Some transequatorial stations were used to help in the analysis. Besides this 60-month period, we also consider the four seasonal periods formed from 15-month composites. Thus winter is taken to be the 15 months of January, February and March in the five year period and so on for the other seasons. The data utilized here form the most complete set available from the M. I. T. General Circulation Data Library. This compilation and its use in general circulation studies are described in some detail by Starr, Peixoto and Gaut (1970), from whom we obtain the computational and analysis techniques to be used in the present investigation.

The horizontal boundary terms have not previously been evaluated from data, as it is usual in general circulation studies to deal with a volume whose upper horizontal boundary is placed at the top of the atmosphere and across which transports are assumed negligible. Rosen (1970), however, has considered northern hemispheric polar caps in which the upper horizontal boundary is moved in the vertical, thereby requiring consideration of the vertical transports of mean zonal kinetic energy across it. Those components of the boundary flux in (1) which represent such transports will be designated, following essentially Starr & Sims (1970), as terms {10}, {11} and {12's}. In addition, the direct advection of zonal kinetic energy across a horizontal boundary will be represented as $\{B\}$. From the discussion of Starr & Sims, it may be seen that it is these four terms which form the complete set of physical vertical transport terms. We now proceed to consider each of these terms individually below.

Results for the individual terms

Since upper-air data is available only in pressure coordinates, it has been necessary to make use of the hydrostatic assumption to transform to such a system. Thus $\omega = dp/dt$, the so-called vertical p-velocity, replaces w, and the radius of the earth, a, is substituted for R.

We begin with:

1. Evaluation at pressure p_1 of

$$\int_{\pi/2}^{0} \frac{2\pi}{g} a^2 \cos^2\phi (\Omega a \cos\phi) [\bar{\omega}] \frac{[\bar{u}]}{a\cos\phi} a d\phi \quad \{10\}$$

where g is the acceleration due to gravity. Note that the latitudinal integration proceeds from the north pole ($\phi = \pi/2$) to the equator ($\phi = 0$) where we have chosen to fix the vertical south-

Table 1. *The 60-month and seasonal-period values of the boundary integral {10} evaluated at various pressure levels (N. H.)*

Units are 10^{20} erg sec^{-1}. Positive values indicate upward transports of zonal kinetic energy.

Pressure (mb)	60 months	Spring	Summer	Fall	Winter
63	0.19	0.38	1.61	−1.58	−2.57
163	−3.59	3.41	1.39	−12.7	−32.9
263	−12.5	0.86	−2.78	−28.2	−88.3
363	−11.3	−0.64	−5.75	−25.1	−74.1
463	−9.87	−2.57	−7.79	−21.7	−52.9
563	−9.49	−3.94	−9.08	−20.1	−39.5
663	−7.81	−3.90	−8.21	−16.4	−25.2
763	−6.08	−3.41	−6.40	−12.8	−15.7
813	−5.00	−3.13	−4.91	−10.4	−10.8
863	−4.52	−3.22	−3.89	−8.89	−8.04
913	−3.88	−3.06	−3.11	−6.91	−5.48
963	−2.06	−1.67	−1.84	−3.26	−2.12

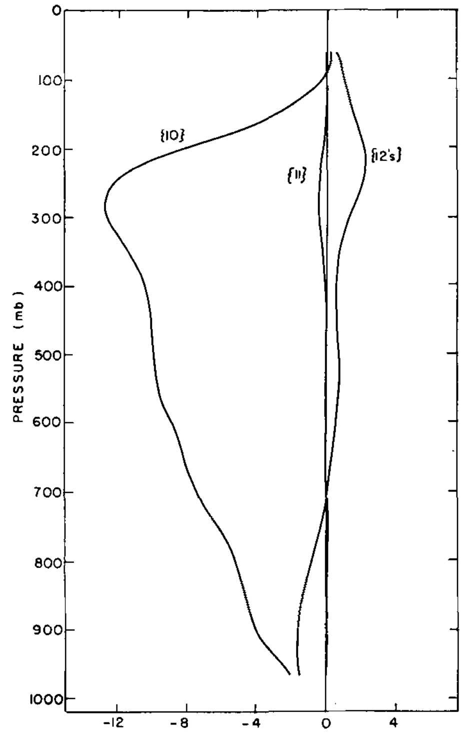

Fig. 1. Vertical profiles of the horizontal boundary integrals in units of 10^{20} erg sec^{-1}. The curves are for the 60-month period. Positive values indicate upward transports of zonal kinetic energy.

ern boundary of our polar cap volume τ. The integral {10} represents the vertical transport of the kinetic energy of the mean zonal flow accomplished through the work done by the stress component associated with the rotation of the earth, Ω, acting across the horizontal surface at p_1. This boundary term, involving as it does the earth's rotation, appears only in the symmetrical form of the zonal kinetic energy equation. As is also true for the other terms in this equation which involve the relatively large quantity $(\Omega a \cos \phi)$, evaluation of {10} results in large numbers which are sensitive to errors made in determining the mean meridional flow, $[\bar{v}]$, from which the mean vertical flow, $[\bar{\omega}]$, is obtained through our continuity requirements.

Listed in Table 1 are the values of the boundary integral {10} for every 100 mb increment of pressure (except at low levels) from 963 to 63 mb (the surface has been taken to be at 1013 mb, and the top of the atmosphere, across which it is assumed that the transports go to zero, has been taken to be at 13 mb). The vertical profiles of this integral appear for the 60-month average in Fig. 1, and for the seasonal periods in the first column of Fig. 2. It may be seen that for the 60-month average condition the net transport due to {10} is downward throughout most of the atmosphere, with some small net upward transports to be found in the stratosphere. The predominance of downward transports is to be noticed on a seasonal basis as well, with only spring and summer exhibiting upper level net upward transports.

The meridional cross-sections contained in Figs. 3 and 4 are of use in depicting the spatial distribution of the integrand of {10} for the various time periods considered. (It should be noted that since the horizontal integration made to obtain values for the boundary integrals is performed in the negative sense, i.e., in the direction of decreasing latitude, the interpretation to be given to positive signs which appear in the cross-sections of the integrands of the boundary terms is the opposite of that to be given to positive signs appearing in the tables or vertical profiles of the integrals.) The cross-sections for {10} show that the process has its largest values in the middle and upper troposphere where the mean vertical circulation and the field of mean relative angular velocity

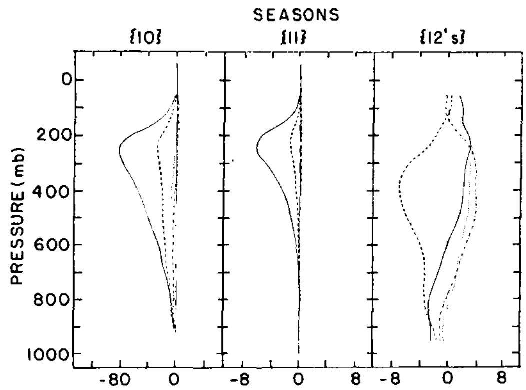

Fig. 2. Vertical profiles of the horizontal boundary integrals in units of 10^{20} erg sec^{-1}. The curves for the various seasonal periods: –·–·–·, spring; · · · ·, summer; – – – – –, fall; ——, winter. Positive values indicate upward transports of zonal kinetic energy.

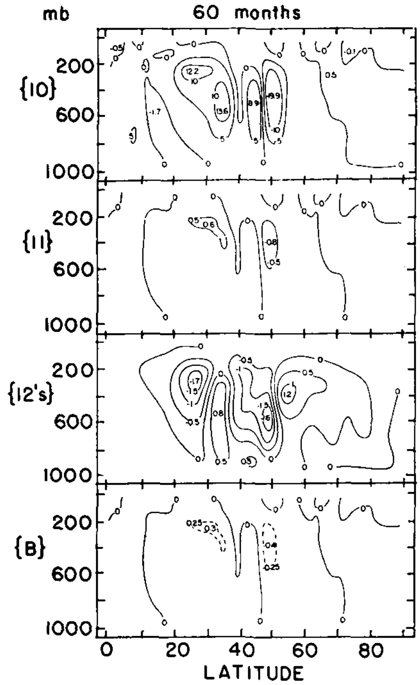

Fig. 3. Meridional cross-sections of the integrands of terms {10}, {11}, {12's} and {*B*} for the 60-month period. Units are 10^{12} erg sec^{-1} cm^{-1}. Positive values indicate *downward* transports of zonal kinetic energy.

tend to be strongest. The cross-sections also show that it is opposing regions of zonal kinetic energy transport which give rise to the values for the horizontal integral given in Table 1. By and large, the downward transports in the middle latitudes dominate the action. Still, since the values of the integrals do result in many instances from the differences between numbers of similar magnitude, which are themselves subject to uncertainty, still better data would be desirable.

2. Evaluation at pressure p_1 of

$$\int_{\pi/2}^{0} \frac{2\pi}{g} a^2 \cos^2\phi [\bar{u}] [\bar{\omega}] \frac{[\bar{u}]}{a\cos\phi}\, a d\phi \qquad \{11\}$$

This integral represents the vertical transport of the kinetic energy of the mean zonal flow accomplished through the work done by the stress component associated with the relative rotation, $[\bar{u}]$, acting across the horizontal surface at p_1. On the basis of the general smallness of the vertical boundary term {8} which similarly involves the relative rotation (see Sims, 1970), it might be supposed that {11} also represents a process which can usually be neglected in energy studies. That this is not strictly the case, however, may be seen from the values of {11} given in Table 2 or plotted in the vertical profiles contained in Figs. 1 and 2. These show that some sizeable transports due to {11} do occur, particularly in the active winter season.

The meridional cross-sections of the integrand of {11} contained in Figs. 3 and 4 reveal patterns which in their general features are similar to those found in connection with {10}. This is to be expected since both terms similarly involve the circulations associated with the mean cells. The major difference between the cross-sections of the integrands of terms {10} and {11} is of course the much smaller values found on those of the latter.

3. Evaluation at pressure p_1 of

$$\int_{\pi/2}^{0} \frac{2\pi}{g} a^2 \cos^2\phi ([\bar{u}^* \bar{\omega}^*] + [\overline{u'\omega'}] + [\bar{\tau}_F]) \frac{[\bar{u}]}{a\cos\phi}\, a d\phi \qquad \{12\text{'s}\}$$

where τ_F represents frictional stresses acting across horizontal surfaces.

This integral represents the vertical eddy transport of the kinetic energy of the mean zonal flow accomplished through the work done by the stress component associated with eddy motions of all scales acting across the

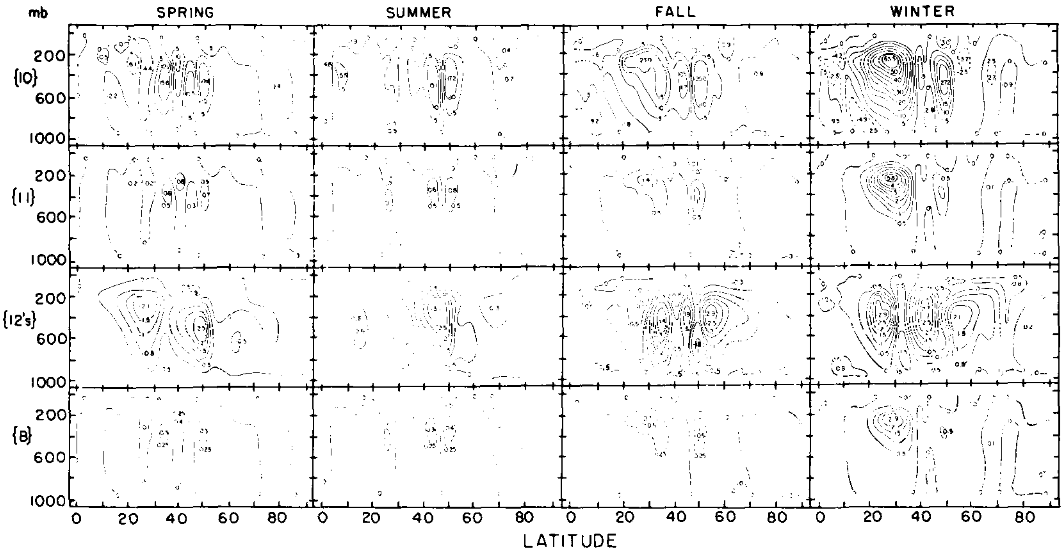

Fig. 4. Meridional cross-sections of the integrands of terms {10}, {11}, {12's} and {*B*} for the various seasonal periods. Units are 10^{12} erg sec^{-1} cm^{-1}. Positive values indicate *downward* transports of zonal kinetic energy.

horizontal surface at p_1. (Although {12's} formally includes molecular effects, it can be readily shown that transports of mean zonal kinetic energy accomplished through molecular scale motions must be decidedly insignificant when compared with those transports arising from turbulent eddy scale motions.) As has been previously discussed, the lack of directly

Table 2. *The 60-month and seasonal-period values of the boundary integral {11} evaluated at various pressure levels (N. H.)*

Units are 10^{20} erg sec^{-1}. Positive values indicate upward transports of zonal kinetic energy.

Pressure (mb)	60 months	Spring	Summer	Fall	Winter
63	0.01	0.02	−0.02	−0.04	−0.11
163	−0.08	0.21	0.11	−0.66	−2.58
263	−0.37	0.21	0.17	−1.37	−6.79
363	−0.21	0.12	0.12	−0.80	−4.12
463	−0.11	0.03	0.07	−0.45	−2.17
563	−0.06	−0.00	0.04	−0.25	−1.16
663	−0.01	0.01	0.03	−0.05	−0.41
763	0.02	0.01	0.01	0.05	−0.11
813	0.03	0.01	0.01	0.09	−0.01
863	0.03	0.01	0.01	0.08	0.03
913	0.02	0.01	0.01	0.05	0.03
963	0.01	0.01	0.01	0.02	0.01

measured vertical velocities necessitates obtaining the vertical processes from the observed horizontal motion field through continuity of mass and angular momentum requirements. The details of how this is actually done in practice may be found in Starr, Peixoto & Sims (1970), who pointed out that the vertical eddies and friction can in this manner only be dealt with as a sum. Thus it is not possible to really know to what quantitative degree vertical eddy actions associated with {12's} may be attributed to a particular scale. Some surmises of a qualitative nature are possible, though. For example, as formulated in the symmetrical zonal kinetic energy equation, positive generations of zonal kinetic energy by vertical eddy actions are attributable to the large-scale eddy transports of *angular momentum* against the vertical gradient of relative angular velocity, since eddies of smaller scales would be expected to act in the usual (positive) viscous manner. Therefore, in regions of such positive generations, we may also associate the nature of the vertical eddy transport of *zonal kinetic energy* with the dominating action of these large-scale eddies. In the regions of negative generation by the vertical eddies, it would seem a matter of conjecture to attempt to distinguish *a priori* between instances in which the small-scale eddies may be dominant

Table 3. *The 60-month and seasonal-period values of the boundary integral {12's} evaluated at various pressure levels (N. H.)*

Units are 10^{20} erg sec^{-1}. Positive values indicate upward transports of zonal kinetic energy.

Pressure (mb)	60 months	Spring	Summer	Fall	Winter
63	0.52	−0.24	−0.42	0.48	1.61
163	1.71	0.05	1.04	−0.75	2.18
263	1.96	3.23	3.55	−3.34	3.47
363	0.64	4.31	3.38	−7.03	2.49
463	0.68	4.40	3.27	−7.20	2.25
563	0.73	3.97	2.70	−5.61	1.11
663	0.36	2.57	1.88	−3.95	−0.21
763	−0.35	1.21	1.30	−3.63	−1.66
813	−0.89	0.40	0.92	−3.79	−2.52
863	−1.37	−0.44	0.32	−3.65	−2.96
913	−1.58	−1.01	−0.29	−3.11	−2.93
963	−1.44	−1.11	−0.55	−2.30	−2.66

over negative viscous actions of large-scale eddies, and instances in which the large-scale eddies may also be acting in the nature of classical turbulence. However, some information about which scales may be important in these negative generation regions can be provided by their spatial distribution. Having now made these somewhat general remarks, we present below a more specific discussion dealing with the results obtained for {12's}.

The values of {12's} for the various time periods and at the selected pressure levels are given in Table 3. Vertical profiles of these values are contained in Figs. 1 and 2. The conditions for the 60-month average show low level downward transports which give way to mid and upper tropospheric upward transports. After reaching a maximum, these upward transports then diminish in strength as the top of the atmosphere is approached. The nature of this pattern is essentially repeated for all the seasonal periods except fall, which exhibits strong *downward transports* throughout the extent of the troposphere. It is of interest to note that fall has also been shown, by Starr, Peixoto & Sims (1970), to be distinguished from the other time periods by the large amounts of *negative generation* yielded in this season by the vertical eddies. On the other hand, spring has been shown to exhibit the maximum of such *positive generation* of kinetic energy by the vertical eddies; and now we find here that the largest *upward eddy transports* of kinetic energy also occur in this season. Thus the vertical eddies, in both their internal generation and boundary transport processes, exert their largest influence in the seasons in which the general circulation undergoes the greatest overall acceleration (fall) or deceleration (spring), with the vertical eddies acting in such a manner so as to moderate these overall changes.

Turning our attention now to the cross-sections of the integrand of {12's} presented in Figs. 3 and 4, we find that for the 60-month average condition there exist two centers of upward transport, located at 27° N and 47° N, separated by a tongue of downward transports. These regions of upward transport, which extend to jet stream levels where vertical eddy long-term positive generations of kinetic energy have also been found (again see Starr, Peixoto & Sims, 1970), most probably reflect at these upper levels the actions of large-scale eddies, as per our earlier discussion above. The general pattern of two distinct cells of upward transports is also to be found in all the seasonal cross-sections except in the summer, where the two cells apparently merge as the intervening tongue of downward transports all but disappears. It is somewhat remarkable that on the fall cross-section, amidst its vast areas of downward transports, there still persists, centered at 49° N, a distinct remnant of the northern mid-latitude upward transport regime. Further study is required for an explanation of the existence of this cell.

The cross-sections for all the time periods consistently show a predominance of downward eddy transports in the lowest atmospheric layers, where Rosen (1970) has also found the dominant vertical eddy generations of zonal kinetic energy to be negative (see also Starr, Peixoto & Sims, 1970). This being the region next to the surface, it seems likely that these characteristic downward transports owe their existence largely to small-scale eddy and frictional actions. Finally, in connection with surface friction layer considerations, it is interesting to note on the cross-sections that a zero isoline consistently dips to the surface in the region where surface mean easterlies give way to surface westerlies (near 30° N). This may be explained by the fact that in this region of transition, zonal mean surface winds are generally light, and so with surface frictional effects reduced to a relative minimum here, the needed downward eddy transports are similarly reduced.

Despite the difficulties inherent in obtaining precise values for {12's}, it seems we can state with some confidence that the results presented here show that significant vertical transports of zonal kinetic energy can be accomplished through eddy stress horizontal boundary actions. The importance of such actions as these has not yet been studied sufficiently.

4. Evaluation at pressure p_1 of

$$\int_{\pi/2}^{0} \frac{2\pi}{g} a \cos\phi [\bar{\omega}] \frac{[\bar{u}]^2}{2} a d\phi \qquad \{B\}$$

This integral represents the direct advection of the kinetic energy of the mean zonal flow by $[\bar{\omega}]$ across the horizontal surface at p_1. In its mathematical form, $\{B\}$ is exactly equal to one-half of term {11}. As Starr & Sims (1970) point out, though, these two terms represent two very distinct physical processes. The situation here is completely analogous to that encountered in connection with the meridional transport terms {8} and $\{A\}$ discussed by Sims (1970). Since term {11} has already been treated in some detail, we need deal with $\{B\}$ only briefly.

Meridional cross-sections of the integrand of $\{B\}$ are contained in Figs. 3 and 4; the value of the horizontal integrals may be obtained by halving those given for {11} in Table 2 or Figs. 1 and 2. While it appears that for most levels and time periods advection is a somewhat minor process, this is not always the case, particularly when one considers the winter troposphere. Here the strong winter circulations combine to yield net downward advections of some consequence, with a maximum advection of -3.4×10^{20} erg sec^{-1} occurring across 263 mb. It is to be remembered however that, as discussed by Starr & Sims (1970), there always exists an internal volume integral which will exactly cancel the value for the horizontal boundary integral $\{B\}$.

General Comments

1. Generally speaking, the largest vertical transports of zonal kinetic energy are associated with term {10}. This is particularly noticeable in the results for the fall and winter seasons where {10} seems at most levels to completely overshadow the other terms. However, it should be kept in mind that in the context of the full equation (1), {10} is only one of several component terms which involve the earth's rotation, and the combined *net* effect of these Ω-terms on the overall balance of kinetic energy is *not* so large as to make unimportant other processes represented in (1). In the traditional formulation of the zonal kinetic energy equation, as written for example by Starr, Peixoto & Sims (1970), this net effect of the earth's rotation is measured entirely by the two so-called Coriolis internal terms and there are no boundary terms involving Ω. Terms {11} and {12's} though remain included in this traditional scheme and in fact represent the only horizontal boundary integrals in it. Therefore a knowledge of their behavior during all time periods remains of considerable interest.

2. We now briefly turn attention to the balance of zonal kinetic energy to be found in layers close to the surface; that is, for northern hemispheric volumes in which the upper boundary is at roughly 900 mb or levels closer to the surface. Rosen (1970) has found that the net effect of all the internal and boundary terms which involve Ω in the symmetric form of the balance equation is to contribute positively to the zonal kinetic energy in these volumes. This effect is overcompensated for in all time periods by the positive viscous actions of the vertical eddies internal to the volumes. This net loss of zonal kinetic energy near the surface is then balanced by downward boundary transports of zonal kinetic energy by, again, the vertical eddies, as represented in {12's}. Thus we find that vertical eddies, in both their generation and transport processes, are of great importance in achieving an energy balance in the surface boundary layer. This result appears quite realistic since, after all, the effect of frictional and small-scale actions which are included in the vertical eddy terms should be significant near the ground.

3. By forming the sum of all the physical vertical transport processes, as represented in terms {10}, {11}, {12's}, and $\{B\}$, we are able to find for the 60-month period a level at which there occurs a transition from net downward transports to net upward transports of zonal kinetic energy. It is of interest to point out that the available data in fact yield no more than one such transition level in any one of the time

periods. For the 60-month average condition, this unique level of zero net vertical transport is located at 125 mb, below which large downward transports associated with {10} dominate, and above which the vertical eddies play the major role in yielding net total upward transports. This average condition reflects a balance between considerable seasonal variations. In the spring, the downward transports due to {10} which dominate below the transition level are opposed by upward transports due to {12's} so as to locate the level of the transition to net upward transports at close to 570 mb. In the summer, these opposing transports balance higher in the atmosphere to yield the transition level at roughly 290 mb. In the winter and fall seasons, for which it is to be recalled that term {10} yields very large downward transports, there appears to be no transition to net upward transports below 63 mb, which is the highest level across which we computed the horizontal boundary terms. However, it is quite possible that a transition level existing below 63 mb (perhaps in the vicinity of 100 mb) may have gone undetected in these seasons because of poor or insufficient stratospheric data.

4. Some mention should perhaps be made of the fact that the left hand side of (1) is not, over a small time period, precisely equal to the average time rate of change of the mean zonal kinetic energy, but rather includes an additional term. For the time periods considered here however, this presents no problem since this additional term probably becomes quite small.

5. The results presented in this paper, when combined with those given by Sims (1970), complete the evaluation, with the best data presently available, of the boundary terms of the symmetrical zonal kinetic energy equation. It is planned in future publications to present similar results for the internal processes and to investigate more completely the balance which exists between the internal and boundary terms.

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ВЕРТИКАЛЬНЫЙ ПЕРЕНОС СРЕДНЕЙ ЗОНАЛЬНОЙ КИНЕТИЧЕСКОЙ ЭНЕРГИИ ПО ДАННЫМ ЗА ПЯТЬ ЛЕТ ПО СЕВЕРНОМУ ПОЛУШАРИЮ

Оценивается вертикальный перенос кинетической энергии среднего зонального течения через произвольные горизонтальные поверхности, покрывающие северное полушарие. Вертикальные процессы не измеряются непосредственно, а получаются по наблюдаемому горизонтальному движению с помощью уравнения неразрывности. Найдено, что вертикальные ветры осуществляют значительный перенос посредством напряжений на горизонтальной границе. Характерной особенностью является турбулентный перенос вниз в приземный пограничный слой.