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KINETIC ENERGY AND QUASI-BIENNIAL OSCILLATION

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ABSTRACT

The modulation of the vertical flux of kinetic energy to the stratosphere by the pressure-work effect at 100 mb is compared with variations in the hemispheric kinetic energy, the horizontal momentum and heat transports at "low" latitudes, and the tropical zonal wind and temperature for the lower stratosphere. It is deduced that the variation of the vertical flux of geopotential is in phase with the kinetic energy in the lower stratosphere and is statistically related to the time rate of change of the horizontal transports of heat and momentum at 30°N. The association of these results to the general circulation of the lower stratosphere is considered.

1. INTRODUCTION

Although the major emphasis in the recent literature concerning the cause of the quasi-biennial oscillation has tended to focus on the equatorial regions of the lower stratosphere (Tucker 1964, Wallace and Holton 1968, Lindzen and Holton 1968, Reed 1964, Newell 1964), it has long seemed to me that the global aspect of this cycle as described by Landsberg (1962), Angell and Korshover (1964), and Labitzke (1965) to name just a few, is also worthy of major consideration. In this regard, Newell (1964) has pointed out that a possible link between tropospheric phenomena and those in the stratosphere is the dynamic coupling between the two regions in the form of the kinetic energy transfer by the pressure-work term at the boundary. This term has been shown to be of major importance to the dynamics and structure of the stratosphere both by calculations of the kinetic energy budget (e.g., Oort 1964, Miller 1967) and by diagnostic evaluation of the potential vorticity equation (Matsuno 1970).

In a previous paper treating the subject (Miller 1970), we have shown that there is, indeed, evidence for a modulation of this energy transfer, principally in the very large-scale waves (zonal wave numbers 1–4). In particular, it was found that the energy flux by the sum of waves 1–4 appeared to be maximized when the easterly wind phase was propagating downward in the Tropics. Left unanswered at that time, however, was the question as to how this energy transfer is related to other parameters in the lower stratosphere such as the horizontal eddy momentum and heat transports and the associated midlatitude wind and temperature fields. For example, we might expect that an increase in the vertical flux of eddy kinetic energy would result in an increase of the magnitude of the eddies in the lower stratosphere which consequently might result in an increase in the horizontal eddy fluxes of heat and momentum. The purpose of this paper, then, is to compare this modulation in the kinetic energy transfer with the hemispheric kinetic energy, the horizontal eddy transports of heat and momentum at "low" latitudes, and the tropical zonal wind and temperature for the lower stratosphere.

While height-time sections of zonal wind and temperature are employed as an indication of the state of the oscillation in the Tropics, the present study is distinguished from its predecessors by the availability of Northern Hemisphere objective height and temperature analyses for use in the above dynamic computations (Finger et al. 1965). This results in more complete analyses than heretofore possible by station analyses and calculation of transient eddy components only. It suffers, however, in that the calculations of heat and momentum transport are generally considered reliable only north of about 30°N.

Although 30°N cannot be considered a tropical latitude, the results of Wallace and Newell (1966) suggest that the oscillations of the horizontal transports are in phase down to the Equator although the amplitudes certainly are not constant. Our results, then, should be indicative of the general phase relationship of these horizontal forcing terms to the other parameters.

The National Meteorological Center Northern Hemisphere analyses of the 50-, 30-, and 10-mb pressure surfaces for every odd-numbered day for the period January 1964 through March 1969 have been subjected to zonal harmonic analysis. Harmonic coefficients of the geostrophic wind components and temperatures were determined; and kinetic energy and angular momentum and heat transports were computed in the wave-number domain. Twelve-month running mean values of the monthly means of the latter quantities form the basis for the present study. From April 1969 on, satellite data from the SIRS A instrument (Smith et al. 1970) have been incorporated into the objective analyses. Because it is not clear at this time if the inclusion of these data alters the computational results in any manner, these months were not included in this study. An investigation of this matter is in progress.

2. LIST OF SYMBOLS

a radius of earth,
c_p specific heat of air at constant pressure,
f Coriolis parameter,
g acceleration of gravity,
$K(n)$ kinetic energy per unit mass per wave number,
n wave number,
p pressure,
T temperature,
T_H flux of heat per unit time per unit pressure difference,
T_m flux of relative angular momentum per unit pressure difference,
u,v eastward and northward components of velocity,
z height,
θ potential temperature,
λ longitude,
ϕ latitude,
ω individual rate of pressure change, dp/dt,
$[(\ )]$ zonal averaging operator defined by

$$[(\ )]=\frac{1}{2\pi}\int_0^{2\pi}(\ )d\lambda,$$

$(\ )^*$ departure of ( ) from zonal mean; that is, $(\ )^*=(\ )-[(\ )]$, and

Fourier transform pairs

Variable	u	v	T	θ
Spectral function	$U(n)$	$V(n)$	$T(n)$	$\theta(n)$

3. COMPUTATION PROCEDURE

Following the notation of Miller and Johnson (1970), the vertical transfer of eddy kinetic energy into a region by the mechanical work done at the boundary (pressure coordinates) is approximated by

$$[\omega^*z^*]=\left(g\frac{\partial[\theta]}{\partial p}\right)^{-1}u(0)f\sum_{n=1}^{\infty}\{V(n)\theta(-n)+V(-n)\theta(n)\}. \quad (1)$$

Physically, eq (1) states that a northward transport of heat, which is associated with a westward tilt of the horizontal eddies, results in an upward flux of kinetic energy. The approximations employed in arriving at the above equation, along with an evaluation of the accuracy of this technique and a comparison with independent data, are given by Miller and Johnson (1970), and Miller (1970). Because the energy fluxes are greater in the larger scale waves and diminish rather rapidly with increasing wave number, these calculations are restricted to the planetary wave numbers 1–4.

The meridional flux of relative angular momentum across a latitude wall per unit time is given by

$$a\cos\phi\int_0^p\int_0^{2\pi}a\cos\phi uv\frac{d\lambda dp}{g}. \quad (2)$$

When expanded into Fourier harmonics, this flux by the "eddies" of relative angular momentum per unit time per unit pressure difference ($n\neq 0$) becomes

$$T_m(\phi)=\frac{2\pi a^2\cos^2\phi}{g}\sum_{n=1}^{\infty}\{U(n)V(-n)+U(-n)V(n)\}. \quad (3)$$

Similarly, the meridional flux of heat becomes

$$T_H(\phi)=\frac{2\pi c_p a\cos\phi}{g}\sum_{n=1}^{\infty}\{V(n)T(-n)+V(-n)T(n)\}. \quad (4)$$

The kinetic energy per unit mass as a function of wave number is expressed as

$$K(n)=\{|U(n)|^2+|V(n)|^2\}+(1/2)U^2(0). \quad (5)$$

In all computations, the height and temperature analyses, originally referred to the 1,977-point National Meteorological Center (NMC) grid, were transferred to a geographic grid (i.e., meridian-parallel intersections at every 10° long. and 5° lat. from 17.5° to 82.5°N). All calculations were then made on the geographic data with the assumption that the flow was geostrophic.

The determinations of the kinetic energy are made at 50, 30, and 10 mb and the vertical flux of kinetic energy at 100 mb; both are integrated over the Northern Hemisphere, although the energy fluxes were then divided by the area of integration so as to be consistent with the units of other investigations. The horizontal transports are calculated at 30°N for the 50-, 30-, and 10-mb levels.

Although the vertical energy flux is essentially restricted to the planetary waves in agreement with the theory of Charney and Drazin (1961), no such wave cutoff could be effectively stipulated for several of the other quantities under consideration. Hence, all other computations are presented as the summation over wave numbers 1–15, essentially the total eddy component. Computations of each quantity in the individual wave numbers did not indicate sufficient information to warrant their presentation. It should be realized, though, that, since the amount of radiosonde data available for the analysis on any given day generally decreases with altitude, the analyses for 50 mb may be expected to be consistently more accurate than those for 30 mb, and both to be more accurate than those for 10 mb.

4. RESULTS

Rigorously, the time rate of change of eddy kinetic energy within a particular pressure layer is related not just to the vertical energy transfer at one boundary but to its divergence. However, because the computational requirements are so extensive and because the static-stability term is relatively more variable at the higher levels, the calculations of this energy transfer were limited to the 100-mb level (Miller 1970). Our results, then, are meant to be indicative of the dynamic forcing of the upper levels by the troposphere.

Following the notation of Perry (1967), the time rate of change of the eddy kinetic energy in the wave domain integrated over an arbitrary mass of the atmosphere is

$$\frac{\partial}{\partial t} K(n) = BKE(n) + LK(n) + CK(n) + BGE(n) + CE(n) - DE(n) \quad (6)$$

where

$BKE(n)$ represents the net convective influx of eddy kinetic energy across the boundaries;
$LK(n)$ describes the internal transfer of kinetic energy between wave numbers and is identically equal to zero when summed over all wave numbers;
$CK(n)$ represents the transfer of kinetic energy from the zonal mean flow to the eddies;
$BGE(n)$ represents the net transfer of eddy kinetic energy across the boundaries by the pressure-work term;
$CE(n)$ is the conversion from eddy available potential energy to eddy kinetic energy; and
$DE(n)$ represents the loss due to friction.

Figure 1 shows the 12-mo running mean of the monthly averaged eddy kinetic energy at 50, 30, and 10 mb along with the 12-mo running mean of the monthly averaged vertical flux of geopotential for the sum of wave numbers 1–4, the latter excerpted from Miller (1970). A negative value of the energy transfer at 100 mb represents a positive transfer *to* the stratosphere. It is clear from the diagram that a year-to-year modulation exists in the eddy kinetic energy with peaks in 1965 and 1967 at all three levels with an amplitude of about 10 percent of the mean value. Significantly, the energy transfer at 100 mb also peaks at approximately the same time periods with an amplitude of about 10 percent. This is sufficient to account for the above variation.

Lag correlations (up to 12 lags) were computed between the filtered monthly values of the energy flux and the eddy kinetic energy at all three levels. In each case, the maximum correlation appeared at lag zero with the values −0.89, −0.83, and −0.70 for 50, 30, and 10 mb, respectively. Statistically, for 49 observation pairs the 0.001 level of significance (Brooks and Carruthers 1953) is about 0.45 which is exceeded at all three levels. Again, the negative sign is due to the fact that a negative value of $[\omega^* z^*]$ corresponds to a positive input of energy to the lower stratosphere.

Physically, however, this phase relationship states that the energy input into the stratosphere is maximized when the time rate of change of the eddy kinetic energy is equal to zero. Hence, it is clear that this modulation in the boundary flux is not the sole contributing factor to the kinetic energy variation and that the other terms in the kinetic energy equation must be taken into account, including the transfer at the upper boundary. The complete depiction of these terms, however, is beyond the scope of this study.

In support of this general concept that the quasi-biennial oscillation is manifested in other components of the energy budget of the lower stratosphere, figure 2 illustrates the 12-mo running mean of the monthly averaged zonal kinetic energy ($n = 0$) at the same levels. As in the case for the eddy kinetic energy, maxima appear in 1965 and 1967 and, as before, correlation coefficients were calculated between the vertical energy transfer and the $K(0)$ for 50, 30, and 10 mb. The maximum correlation coefficients were respectively −0.80, −0.79, and −0.85, again at lag zero.

Although we were not able to calculate the remaining terms in the kinetic energy equations, it is clear that the energy exchange term between eddy kinetic and zonal kinetic energy in itself cannot account for the above variations. For example, by the above phase criterion $\partial K(0)/\partial t = 0$, $n \neq 0$, when the eddy energy input is essentially maximized. If this vertical energy transfer were to be totally transferred to zonal kinetic energy, then we would expect $\partial K(0)/\partial t$ to be positive. That it is observed to be approximately zero indicates that we must also consider the remaining terms of the complete energy equations.

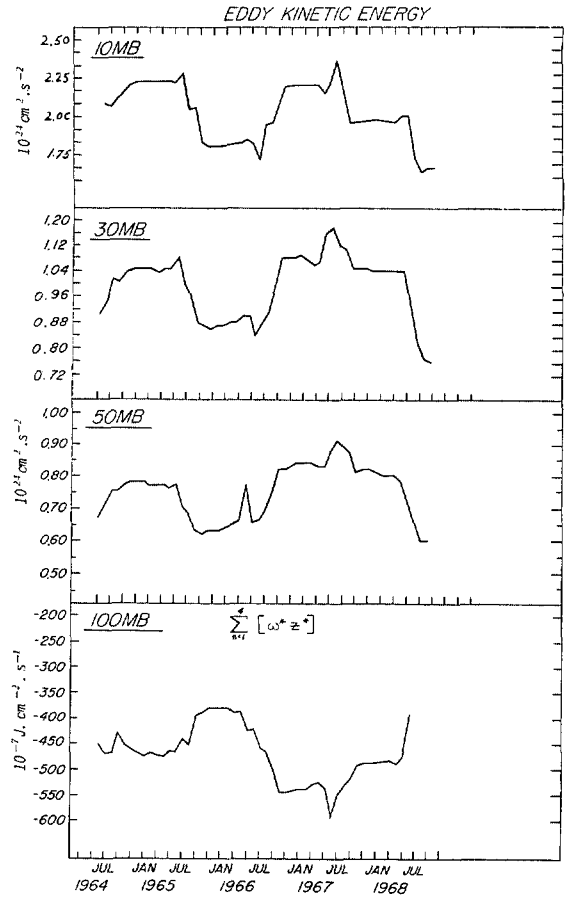

FIGURE 1.—The 12-mo running means (plotted at the center of the time period) of monthly averaged 10-, 30-, and 50-mb eddy kinetic energy (wave numbers 1–15), and the vertical flux of geopotential (wave numbers 1–4). A negative value of $[\omega^* z^*]$ corresponds to a positive input of energy to the lower stratosphere. Units: kinetic energy (10^{24} cm^2·s^{-2}), vertical flux of geopotential (10^{-7} J·cm^{-2}·s^{-2}).

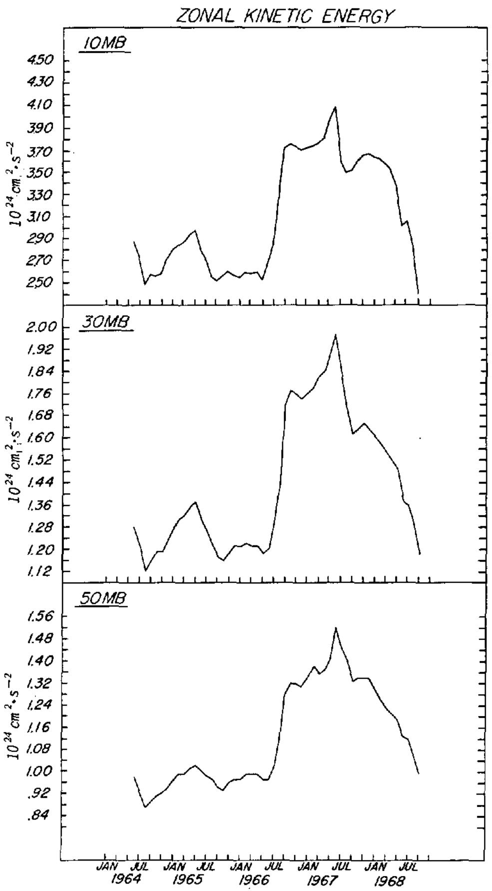

FIGURE 2.—The 12-mo running means of monthly averaged 10-, 30-, and 50-mb zonal kinetic energy. Units: 10^{24} cm^2·s^{-2}.

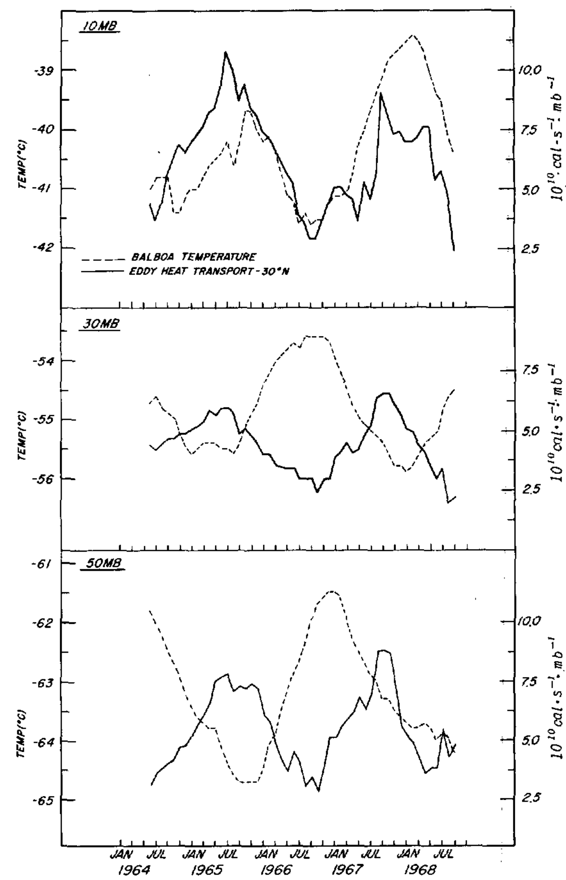

FIGURE 3.—The 12-mo running means of monthly averaged 10-, 30-, and 50-mb temperatures at Balboa, Canal Zone; and the eddy heat transport at 30°N by the sum of wave numbers 1–15. Units: temperature (°C), heat transport (10^{10} cal·s^{-1}·mb^{-1}).

For example, we note that in the total eddy kinetic energy equation [eq (6)] the $BKE(n)$ term is about an order of magnitude smaller than the $BGE(n)$ term (e.g., Oort 1964) and that $LK(n)$ is identically equal to zero when summed over all wave numbers. Therefore, if $BGE(n)$ is maximized or minimized when $\partial K(n)/\partial t$ is equal to zero, then the mechanical forcing at that time must be balanced by the sum of $CK(n)$, $CE(n)$, and $DE(n)$. From the argument above, however, it is unlikely that the balance occurs solely through the $CK(n)$ term, hence it appears that the remaining terms, $CE(n)$ and $DE(n)$, must be included in this analysis.

Unfortunately, measurements of these quantities over an extended time period are not available at this time. It is recognized, however, that the major stratospheric circulation changes occur during the midwinter warming phenomenon (e.g., Finger and Teweles 1964) and the winter-to-spring transition warming period (e.g., Johnson and Gelman 1968). It would appear, then, that a study of the year-to-year modulation of the magnitude and sign of the elements of the stratospheric energy cycle should focus on these particular periods.

Turning now to the relationship between the kinetic energy and the horizontal transports of heat and momentum, we see in figure 3 the 12-mo running mean values of the eddy heat transport at 30°N and the observed temperatures at Balboa, Canal Zone (9°N, 80°W). Immediately apparent is that, although the phase of the Balboa temperatures appears to be a function of height, the phase of the heat transport variation seems to be approximately constant with height. The oscillation of the eddy flux of heat, then, while having an amplitude of roughly 30–50 percent of the average transport, cannot account for the phase variation with height of the temperatures in the Tropics.

One feature which was noted in another study (McInturff et al. 1971), but is of concern here, is the particular temperature phase relationship at these levels during this period in the Tropics. As can be seen in figure 3, the 10-mb temperature oscillation precedes that at 30 mb by about one-half period, considerably greater than noted for previous years (e.g., Wallace and Newell 1966). As noted by McInturff et al. (1971), this phase shift between 10 and 30 mb appears to occur in the period 1962–63 so that the possibility exists that it *may* be related to the now infamous volcanic eruption at Mt. Agung in March 1963 (e.g., Newell 1970). That the phase shift maintains itself well into 1969, however, suggests that its cause may be more dynamic in nature. In any case, it is apparent that our results may be considered representative of only the particular period under study and should not be extrapolated to other periods. It is worthy of note that results from Ascension Island exhibited similar behavior (McInturff et al. 1971).

Looking now at the phase relationship between the heat transports and the Balboa temperatures at the three levels, the absolute maximum correlations at 50, 30, and 10 mb, respectively, were −0.69 at lag −3 mo; −0.86 at lag −1 mo; and 0.35 at lag 0. A negative lag indicates that the heat transport leads the temperature by that lag.

The implication is that, at 50 mb, the heat transport is relatively large when the temperatures are decreasing and vice versa although the lag of 3 mo is not really a quarter period. At 30 mb, this same general association is even more pronounced, but again the phase lag is only 1 mo so that other terms in the thermodynamic equation must be considered for the time rate of change of temperature (e.g., Reed 1964). The results at 10 mb reflect the phase difference in the temperatures between 10 and 30 mb referred to above. As discussed above, however, it is not clear at this time whether this 10–30-mb phase shift is dynamic or radiative in origin.

The relationship between the mechanical energy input and the horizontal transport of heat is perhaps best illustrated by correlation coefficients at the various levels. For 50, 30, and 10 mb, respectively, the maximum correlations are +0.56 at lag +8 mo, +0.82 at lag +9 mo, and +0.67 at lag +4 mo. The indication, then, is that the vertical energy influx to the stratosphere is relatively large when the horizontal heat transport is increasing and is relatively small when the latter is decreasing. This is suggestive of a relationship between the energy flux and the time rate of change of the meridional eddy flux of heat rather than the heat transport itself and vice versa.

Looking next at the wind components, we see in figure 4 the 12-mo running-mean filtered values of the zonal wind component at Balboa and the eddy momentum transport at 30°N for the three standard levels. It is of particular interest that, in contrast to the Balboa temperatures, the zonal wind appears to maintain its historical phase relationship between the three levels. This, in fact, is one of the points in favor of the Mt. Agung influence hypothesis (e.g., McInturff et al. 1971).

With respect to the horizontal eddy momentum transports, the depiction of any oscillation is considerably more confused than that of the heat transports by the very apparent trend in the data from 1964–68, best recognized at the lower two levels. While it is extremely difficult to pinpoint all the maxima and minima in these data, it appears that certain statements can be made, especially if we assume that the phase of the variation is constant with height.

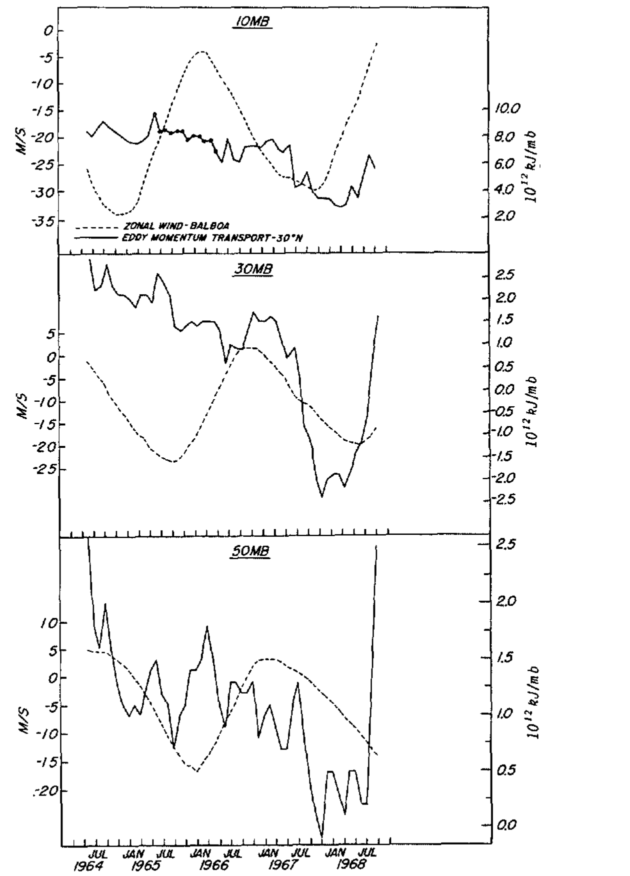

FIGURE 4.—The 12-mo running means of monthly averaged 10-, 30-, and 50-mb zonal winds at Balboa, Canal Zone; and the eddy momentum transport at 30°N by the sum of wave numbers 1–15. Units: wind (m/s), momentum transport (10^{12} kJ/mb). The dotted portion of the 10-mb momentum transport curve represents questionable data.

The eddy momentum transport curves for 50 and 30 mb (fig. 4) show clearly that definite maxima occur in 1964 and late 1968 with a minimum in late 1967–early 1968. The phases of these maxima and minima, however, are opposite to those of the heat transports. If we assume that this antiphase relationship is consistent, then we should seek a minimum in middle–late 1965 and another maximum in late 1966–early 1967. Although the evidence is certainly not overwhelming, there is an indication of a leveling off of the trend at about the appropriate time, indicating a disruption of the continued decrease. The curve for 10 mb does, indeed, indicate general substantiation of this assumed configuration with the exception of 1965–66 when no minimum is in evidence. Perusal of the individual wave number data, however, indicated that, in December 1965, the momentum transport was about three times the value for any other December during the 5-yr period. Investigation of the synoptic analyses for this period indicated that a "minor" warming existed in the lower stratosphere. As usual, however, the amount of data available at 10 mb was generally skimpy so that it is uncertain whether the analyses can be considered totally reliable. As indicated on the curve for 10 mb, the period influenced by the very large value in December 1965 is just at that time when we seek a minimum in the transports.

Although the above argument is admittedly weak, if we assume it to be correct, then the following general phase relationships hold between the momentum transport and the zonal wind. At 10 mb, the momentum flux seems to lag the zonal wind field so that maximum transport occurs when the wind is decreasing and minimum flux when the wind is increasing. At 30 mb, however, the two parameters are generally in phase and, as would be expected, at 50 mb the momentum transport leads the wind variation. This, again, demonstrates the need for consideration of other terms in the explanation of the vertical phase propagation of the zonal wind (e.g., Wallace and Holton 1968, Lindzen and Holton 1968). In a similar manner, the vertical energy flux is relatively large when the horizontal momentum transport is *decreasing* and vice versa.

With respect to the observed trend in the momentum fluxes, it is worth noting that the basic operational analysis program used to construct the charts remained essentially unchanged during this period. Of course, the available data at each level has tended to increase during this period, but the apparent momentum flux increase in late 1968 suggests that the downward trend is not associated with this fact. Moreover, the appearance of apparent long-period cycles in observed winds and temperatures has been noted by other authors (e.g., Angell and Korshover 1967). It is not clear at this time why such a large trend in the momentum transports at 30°N is not reflected in the zonal winds. The existence of this trend possibly explains why previous investigators of the eddy momentum transport have had different degrees of success in finding a modulation of the eddy momentum transport in their data (e.g., Hirota and Sato 1970, Tucker 1964).

It is recognized that this concept, that modulations of the horizontal eddy transports of heat and momentum are out of phase, has not really been investigated till now and was not evident from the data of Wallace and Newell (1966). Because the configuration of the momentum transports is not well defined, however, it is logical to seek further verification in other parameters, such as the mean zonal wind and temperatures in midlatitudes. The results of this comparison at 60°N for the wind and 62.5°N for the temperature at 50 mb is shown in figure 5. As is evident in this diagram, the two fields are opposite in phase; a fact substantiated by a maximum correlation coefficient of −0.74 with no lag. We note also that the range of the mean zonal wind is about 5 m/s but that of the zonal temperature is about 1.5°C. At higher altitudes, the zonal wind maintains the same phase, but the temperature pattern becomes more random; hence, the curves for 30 and 10 mb are not presented. It is not clear whether the *tendency for randomization of the temperatures with* height is a real phenomenon or simply a reflection of the

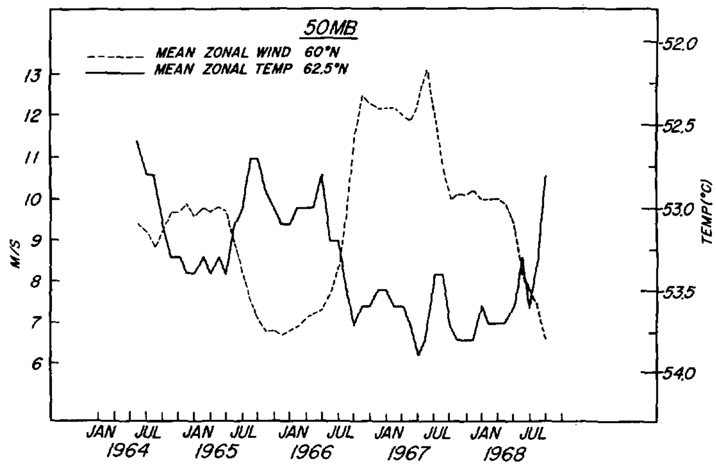

FIGURE 5.—The 12-mo running means of monthly averaged 50-mb mean zonal wind at 60°N and mean zonal temperature at 62.5°N. Units: wind (m/s), temperature (°C).

decreased number of observations and increased noise level.

Looking next at the relationship of the heat and momentum transports at 30°N to the midlatitude zonal winds and temperatures, we see that, in general, the transports lead the parameters. That is, the transports are generally maximum as the parameters are increasing and minimum when the parameters are decreasing. The wind-momentum flux correlation would not be meaningful because of the large trend in the momentum transports, but the maximum heat transport (30°N)-$T_{62.5°N}$ correlation was −0.37 at lag +5 mo, which is significant at the 95-percent level.

5. REMARKS

The purpose of this study is to show that a very strong, albeit complex, relationship exists between the dynamic coupling of the troposphere and stratosphere and the quasi-biennial oscillation in the lower stratosphere. Two rather surprising aspects of our results are: (1) the modulation of the vertical flux of geopotential at 100 mb is in phase with the kinetic energy in the lower stratosphere rather than its time rate of change and (2) this same modulation is related to the time rate of change of the horizontal transports of heat and momentum at 30°N rather than to the transports themselves.

In view of the results of some of the recent analytical and numerical models (e.g., Matsuno 1970, Dickinson 1968) that treat this general subject matter, we would have expected just the opposite relationship (i.e., opposite to what was found in (1) and (2) above). The reason for the disparity, we believe, lies in the fact that these models assume a basic state that is stable with respect to axially asymmetric disturbances (Charney and Stern 1962) whereas in the real atmosphere stratospheric warmings occur in midwinter and during the winter-spring transition. The suggestion, then, is that the effect of the modulation of the vertical flux of geopotential is, in turn, modified by the dynamic stability characteristics of the stratosphere such that a modulation of the general energy transfer processes of the stratosphere as a whole occurs (e.g., Newell et al. 1969, Wallace 1967). While this schematic representation does not explain why the quasi-biennial oscillation in the Tropics propagates downward with time, it does tend to link the tropical phenomenon with other observed variations. The manner by which these modulations occur remains the subject of future effort.

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