Eddy fluxes and the biennial stratospheric oscillation

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SUMMARY

The zonal wind together with the eddy transports of momentum and heat at low and middle latitudes in the stratosphere of the Northern Hemisphere are found to display a two year periodicity which results from a sequence of alternating weak and strong winters, where 'weak' and 'strong' refer to the intensity of the eddy circulations at middle latitudes. At levels above 30 mb, the modulations in the eddy momentum transports appear to be strong enough to account for the year to year changes in westerly momentum in the tropics.

Similarities between the stratospheric oscillation and the biennial pulse in tropospheric data suggest an interrelation between the two phenomena. The two year periodicity may not be a permanent feature of the general circulation.

1. INTRODUCTION

The observational and theoretical aspects of the atmospheric biennial oscillation have been recently reviewed by Reed (1965) and have been extensively presented and debated in this journal (for example by Ebdon, (1960; 1961), Reed (1964), and Tucker (1964; 1965). Reiteration will therefore be kept to a minimum. Two models of the mean meridional wind field in the tropics have been suggested to explain various features of the oscillation. Reed, who was primarily concerned with the heat budget, proposed a system of downward propagating mean meridional cells whereas Tucker has stressed the momentum changes produced by modulated quasi-horizontal eddy fluxes acting in conjunction with a constant cell structure. Tucker (1964; 1965) presented some computations of eddy momentum transport based on a small data sample to demonstrate that a modulation of the correct period did exist. Concomitantly and independently it was suggested by Newell (1964a) that the zonal wind, temperature and total ozone variations in the tropical and subtropical stratosphere were all consistent with a modulation of the eddy fluxes and that because the stratosphere is a region of forced motion the modulation would be expected to be present also in the ultimate driving region, namely the middle latitude troposphere. Consequently an examination of the momentum and heat fluxes over a long time period for a large number of stations in both stratosphere and troposphere between about 25°S and the North Pole was begun. The object of the present paper is to report and discuss the character of the biennial oscillation in more detail including the momentum and heat flux computations obtained from the first part of the investigation, which covers the Northern Hemisphere stratosphere to about 45°N for a five year period.

2. THE HEAT AND MOMENTUM FLUX COMPUTATIONS

Five years of radiosonde data for the period May 1958 to April 1963, at 0000Z, for 704 stations in the Northern Hemisphere have been processed by Massachusetts Institute of Technology, under the direction of Professor V. P. Starr, with the help of Travelers Research Center. From the 704 stations 250 which report fairly regularly at levels above 100 mb were selected for the present study. This number is large enough to make a station list rather cumbersome, so a map showing their distribution (Fig. 1) has been substituted. On viewing the map one is struck by the relative scarcity of stations over the Eurasian continents. Due to transmission delays which interfered with routine processing, most of the Russian and Chinese data for high levels during these years were never decoded in the United States. It is hoped that some of them can be recovered for use in later studies. Any information regarding the availability of this data would be greatly appreciated.
Figure 1. Distribution of stations used in the study. Latitude bands into which stations were grouped are denoted by Roman numerals. Blank areas denote regions where data are nonexistent or unavailable.

The parameters under consideration are wind and temperature at 100, 50, 30, 20, 15 and 10 mb. The stations have been grouped into 13 latitude belts which are outlined in Fig. 1. Table 1 shows the actual number of observations containing both wind and temperature which are available during the five year period as a function of latitude belt and pressure level.

<table>
<thead>
<tr>
<th>TABLE 1. NUMBER OF INDIVIDUAL OBSERVATIONS CONTAINING BOTH WIND AND TEMPERATURE AS A FUNCTION OF LATITUDE BELT AND LEVEL</th>
</tr>
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<tbody>
<tr>
<td>100 mb</td>
</tr>
<tr>
<td>52°N (V)</td>
</tr>
<tr>
<td>47°N (VI)</td>
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<tr>
<td>42°N (VII)</td>
</tr>
<tr>
<td>37°N (VIII)</td>
</tr>
<tr>
<td>32°N (IX)</td>
</tr>
<tr>
<td>28°N (X)</td>
</tr>
<tr>
<td>22°N (XI)</td>
</tr>
<tr>
<td>14°N (XII)</td>
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<tr>
<td>8°N (XIII)</td>
</tr>
</tbody>
</table>

Monthly mean values, , were computed at each station for the following quantities:

- \( u \) zonal wind component
- \( v \) meridional wind component
- \( u' u' \) northward momentum transport by transient eddies
- \( v' T' \) northward heat transport by transient eddies
- \( \sigma_u \) standard deviation of the zonal wind component
- \( \sigma_v \) standard deviation of the meridional wind component
- \( \sigma_T \) standard deviation of temperature.
Station values of each of the above quantities were then combined so as to obtain average values, \([\bar{\tau}]\), for each latitude belt. The station values were weighted by the number of reports for the month so that, for instance, a station which reported on 20 days of the month would be ten times as influential as a station which reported only twice.

Strictly speaking, a zonal average could be most accurately derived by drawing maps for each quantity at each level and combining values at equally spaced grid points. Obviously, that is impossible in this case, due to the absence of data over large portions of each latitude belt. A slightly cruder method which also pays heed to longitudinal representation would be to weight each station by the longitudinal extent which its data represent, so that stations in regions of sparse data would be more influential than those which are densely spaced. However, if isolated stations are used to represent the vast areas which surround them large errors will still result, since over the space of a few hundred miles, conditions can change markedly. While the method used in this study fails to produce mean quantities which are uniformly representative with respect to longitude, it does have the distinct advantage that random errors are minimized by the equal weighting of all observations.

The above arguments do not fully justify what has been done. The results are valid if, and only if, the quantities thus calculated truly represent means for their respective latitude belts. There is reason to hope that this may be the case for the parameters used in this study. Buch (1954) noted that latitudinal means of heat and momentum transports as calculated by averaging together station data were almost identical to those obtained from map analyses. Moreover, some degree of zonal symmetry is to be expected in quantities connected with the biennial wind oscillation, which is itself zonally symmetric. For the present, the latitudinal means derived in this study can be said to apply mainly to the North American sector, from which the great majority of the data are taken.

A similar problem arises in the time averaging for stations with only a few soundings in a month. Several soundings spaced far apart in time yield a more reliable monthly

Figure 2. Twelve month running means of zonal wind. Units are in m sec\(^{-1}\). The twelve month averaging periods are centred on the dates indicated at the bottom of the diagram.
mean than the same number of reports if they should happen to fall on consecutive days, since in the latter case the observations are not really independent of one another. Fortunately, this ambiguity is a problem only for stations with few observations in a given month, and these are given little weight in the zonal means. Therefore this is probably not so serious a problem as that of spatial averaging.

The zonal means were averaged over 12 month intervals for the purpose of smoothing and eliminating the annual cycle. The final product was thus a time series of each of these 12 month running mean quantities for each latitude belt and level.

3. EXTENSION OF THE WIND OSCILLATION INTO MIDDLE LATITUDES

Angell and Korshover (1963) have discussed the properties of the wind oscillation at middle and high latitudes on the basis of spectral analyses of wind data from selected stations. The method of processing the data as outlined above afforded a convenient means of examining the zonal winds in middle latitudes in more detail. Discussion of the winds at lower latitudes is presented by Wallace (1966).

Fig. 2 shows time series of 12 month running means of zonal wind at selected latitudes and levels. A biennial periodicity is present, with a distinct phase reversal at the higher levels around 30°N. Studies of Rofe (1963) and Sparrow and Unthank (1964) for stations at corresponding latitudes in the Southern Hemisphere show an oscillation with a somewhat larger amplitude and no noticeable phase reversal at 30°S.

Figure 3. Twelve month running means of momentum transport by transient eddies, \([u'v']\). Units are \(m^2 s^{-2}\). The twelve month averaging periods are centred on the dates indicated at the bottom of the diagram. Data for the periods 7/57-4/58 and 5/63-12/64 have been incorporated into the curves for tropical regions.
4. RESULTS OF THE MOMENTUM FLUX COMPUTATIONS

Tucker (1964; 1965) has already presented evidence of a periodicity in the transport of westerly momentum by transient eddies. The large data sample available in the present study provided a means of describing this phenomenon in more detail. Fig. 3 shows 12 month running means of \( [u'v'] \) for various latitude bands and levels. The following features are to be noticed:

1. There does indeed appear to be a biennial oscillation in the eddy momentum transports and their latitudinal divergence above the 30 mb level in the tropics and above the 50 mb level at higher latitudes. It is a real feature which shows up in many basically independent sets of data at many different latitudes and levels.

2. Below the 30 mb level the data give little or no evidence for any definite year to year variation in the momentum transports at low latitudes.

3. The oscillation in momentum transports is practically simultaneous at all levels and latitudes where it appears.

4. The amplitude of the oscillation increases with latitude.

The oscillation in \( [u'v'] \) is accompanied by oscillations in the standard deviations of \( u \) and \( v \) (Fig. 4) which have the same phase, which suggests that the momentum flux variation is partially due to a periodicity in the intensity of the eddies. However, at low latitudes, where \( [u'v'] \) changes sign during some parts of the oscillation, the correlation coefficient between \( u \) and \( v \) becomes the dominant factor in the momentum transport fluctuation. Tucker (1964) pointed out that this implies periodic changes in the shape of the disturbances at these latitudes.

![Figure 4](image)

Figure 4. Twelve month running means of momentum transport by transient eddies \([u'v']\), together with corresponding curves for the temporal standard deviations of the zonal and meridional wind components, \( \sigma_u \) and \( \sigma_v \). Units are in \( m^2 sec^{-2} \). The twelve month averaging periods are centred on the dates indicated at the bottom of the diagram.

The 'square wave' patterns centred on the winter months in Fig. 3 suggest that the oscillation in the running means may be due to differences between alternate winters. Fig. 5 which shows actual time series of \( [u'v'] \) at 42°N bears this out. Those winters in which January falls in even years during this period tend to be characterized by larger and more persistent northward momentum transport than odd numbered winters. The summer transports are so small that year to year changes have no noticeable effect on the running mean. Nor is momentum transport the only quantity which shows this effect. Twelve month running means of ozone and temperature at mid-latitude stations in both hemispheres (Angell and Korshover 1964) and zonal winds in the Southern Hemisphere (Rofe 1963; Sparrow and Unthank 1964) reveal the same square wave pattern centred on the winter months. In fact, all parameters studied to date which exhibit a biennial periodicity at mid-latitudes do so by virtue of differences in magnitude between the winters of odd and even years.
5. Results of the Heat Flux Computations

The 12 month running means of the zonally averaged heat fluxes are shown in Fig. 6 at 20 and 50 mb levels for several latitude bands. The data are suggestive of a winter dominated two year periodicity, with winters in which January falls in the even years having the larger values as was the case for momentum transports. Winters with the larger poleward heat fluxes are characterized by colder than normal temperatures in the 20 to 50 mb region at the Equator and warmer than normal temperatures at the same levels in the subtropics. Thus it appears that the biennially periodic component of the heat flux is countergradient; it should be noted that this is contrary to the modelling assumption made by Reed (1964). The data give heating rates associated with the year to year differences of the divergence of eddy heat flux of about 0·02°C per day at 20 mb, which is of the same order of magnitude as the radiative heating rates corresponding to Reed’s 50 and 100 day ‘time constants.’ If these estimates are correct the countergradient eddy heat transport may be large enough to offset the radiative dissipation, in which case the mean meridional motions could be considerably different from those in Reed’s model. In support of Reed’s calculations, it should be noted that the heating rates computed recently by Kennedy (1964) are about an order of magnitude larger than those due to the eddy flux divergences.

It is interesting to note that the winters with large momentum and heat transports are also the winters with large ozone amounts in middle latitudes (see Fig. 7 and Ramanathan 1963). This is to be expected if, as Newell (1964a; c) suggests, eddy transports are responsible for the anomalously high ozone concentrations at middle and high latitudes during the late winter and spring months. It would appear that in the winters of even numbered years the eddy circulations are stronger and transport more momentum, ozone and heat poleward than in the adjacent winters.

Figure 5. Monthly values of momentum transport by transient eddies at 42°N. Units are m² sec⁻¹.

Figure 6. Twelve month running means of heat transport by transient eddies. Units are m°C sec⁻¹. The twelve month averaging periods are centred on the dates indicated at the bottom of the diagram.
Thus far the tendency for various parameters to display somewhat different characteristics in alternate years has been spoken of as a two year periodicity. Lest this term be interpreted in too broad a sense, it would be well to discuss some limitations involved in its usage in describing this phenomenon.

Several authors have pointed out variations in the length of the period from cycle to cycle. A certain amount of noise is inherent in this as in any meteorological data, and thus it is not surprising that no cycle is quite the same as any other cycle. Nevertheless there is a certain regularity common to all the cycles before 1963. From the time-height sections in the companion paper, Wallace (1966), and of Belmont and Dartt (1964), it is evident that at very low latitudes the transition from westerlies to easterlies is always first noticeable at high levels during the late months of the odd years, whereas at higher latitudes the year to year variation is confined to the winter season. Under these conditions, if the period in question is near two years, then it must be exactly two years, regardless of what spectral analyses indicate.

The data since 1963 indicate a subsequent breakdown of the oscillation. The ozone amounts at Arosa (Fig. 7) show a break in the two year pattern which becomes evident in 1964 and 1965. Dyer and Hicks's (1965) data on ozone at Aspendale (38°S) show a similar cessation of the periodicity. The time height sections of zonal wind presented in the companion paper (loc. cit.) show an irregularity which grows increasingly apparent during and after 1963 as do the curves of $u'v'$ in Fig. 3.

Nor is this the only time period during which there are marked departures from a two year periodicity. The ozone amounts at Arosa (Fig. 7) prior to 1952 fail to show any evidence of a regular year to year fluctuation. Unfortunately there are no independent data to substantiate this, and the early ozone measurements are open to some question as to accuracy.

In any case there is reason to believe that the phenomenon under consideration in the stratosphere exhibits intermittent periods of phase locking with the annual cycle. There is a growing body of evidence in favour of an oscillation with similar properties in the troposphere:

(1) Landsberg et al (1963) reported a nearly two year pulse in surface temperatures. The oscillation appears to be mutually in phase in tropical regions, while regions of higher latitude are characterized by an out of phase relationship with respect to the tropics. The amplitudes of the pulse are largest when the pulse extremes coincide with the winter months. The pulse seems to be more organized (i.e. stations at the same latitude are consistently in phase with one another) in some time periods than in others. It is interesting to note that this led Landsberg et al to suggest the possibility that the stratospheric oscillation is also an intermittent phenomenon.
Shapiro (1964) shows evidence of a periodicity of slightly greater than two years in the variance of surface pressures. Again, most of the variance is contributed by the winter seasons.

Teweles (1966) has found a large two year periodicity in the momentum transports at 500 mb by eddies with certain wave numbers. His results are based on data for a time period during which the oscillation is known to have been active in the stratosphere. The year to year differences are almost entirely due to the winter seasons.

7. CONCLUDING REMARKS

The computations of zonally averaged momentum eddy fluxes have demonstrated that in low latitudes at 30 mb and above there is a winter to winter difference in the magnitude of the fluxes that acts in the right sense to produce the observed changes in zonal winds. A similar difference appears at middle latitudes down to 50 mb. In the period studied, winters for which January fell in even numbered years exhibited greater momentum and heat transports by eddies, and greater total ozone at middle latitudes, than winters of odd numbered years. The lack of an observable year to year modulation of eddy fluxes in the region below 30 mb at low latitudes may be real, or it could be due partly to an approach to the atmospheric noise level, which is probably set by small-scale wind fluctuations with uncorrelated zonal and meridional components. The apparent fluxes at these levels are too small to account for the wind changes and therefore the momentum and heat budgets may have to include the effects of mean meridional cells, as suggested by Tucker and Reed. Since certain aspects of the momentum budget appear to be best explained in conjunction with such cells a more detailed discussion of possible driven meridional motions is presented in a companion paper (loc. cit.).

The observations processed to date do not allow a distinction to be drawn between forcing of the biennial oscillation by the heat engine associated with the polar night jet (Newell 1964b), by the tropospheric heat engine, or by a combination of the two; but the fact that a forced motion is implied indicates that the ultimate cause may well be a modulation of eddy energy being supplied to the region, rather than radiative changes in situ. The former could be produced either by a modulation of the energy source itself or by year to year differences in the ability of the atmosphere to transmit this energy to the driven region, i.e. a modulation in the transmissivity of the intervening region to wave energy.

In view of the probable lapses in the oscillation, which may possibly extend over many years, it may not be meaningful to speak of periodicities present in long data records as physical entities and hence care must be taken in interpreting the results of spectral analyses of such data.

It must be noted that the eddy fluxes of heat and momentum computed in this study are based on the contributions of eddies with time scales shorter than one month. The inclusion of the effects of longer period eddies, which is contemplated in the near future, might be expected to modify the results quantitatively, but not qualitatively. Another source of uncertainty lies in the fact that most of the data used in the zonal averages are from North American stations. There are not enough data available from any other geographical region to allow an independent check of the results. However, the fact that the same features are prominent in the time series at all latitudes, even in the tropics where much of the data are from stations in the western Pacific, strongly suggests that the quantities computed herein are representative of the zonal means, at least in so far as their use as indicators of year to year differences is concerned.

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REFERENCES

Buch, H. 1964 Ibid., 21, p. 354.
Dyer, A. J. and Hicks, B. B. 1964 'Hemispheric wind conditions during the year 1950,' Final Rep., Contract AF 19 (122)-153, M.I.T.
Kennedy, J. S. 1964 'Energy generation through radiative processes in the lower stratosphere,' Rep. 11, Contract AT (30-1) 2241, M.I.T.
Newell, R. E. 1964b Ibid., 86, p. 540.
Rofe, B. 1964 Ibid., 90, p. 441.
Teweles, S. 1964 Ibid., 90, p. 328.
Wallace, J. M. 1966 To be published.
To be published.