On the role of mean meridional motions in the biennial wind oscillation

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SUMMARY

Detailed time-height sections and meridional cross-sections of zonal wind are presented for the zonally averaged conditions between 32°N and 20°S. The patterns which appear in the sections vary slowly and systematically with latitude and time. The biennial wind oscillation is evident in the sections, but since 1963, the two year periodicity, as such, has vanished and the wind fluctuations, though still similar in form to the previous ones, have become much less predictable. The sections suggest that the lower edges of westerly regimes propagate downwards more rapidly than those of easterly regimes.

The momentum budget of the region is then examined, term by term, and it is concluded that a mean downward motion is necessary over the Equator to account for the downward propagation of the wind regimes there. It is suggested that the enhanced vertical motion during the descent of westerly regimes at the Equator might account for the observed downward propagation at sub-tropical latitudes. The heat budget is then examined with respect to the vertical motions suggested from momentum considerations. It is found that a heat sink in the equatorial stratosphere would be required to support the vertical motion field. It is shown that enhanced downward motion during the descent of westerly regimes (which the zonal wind data suggest) is necessary to keep the temperature field in geostrophic equilibrium with the wind field.

1. INTRODUCTION

The wind structure of the low latitude stratosphere varies considerably from day to day at a given station, and from station to station on a given day. However, this region possesses the remarkable property that when wind data are averaged over a suitable interval, (e.g., a time average over a month) coherent features emerge which are largely independent of longitude, and vary slowly and systematically with latitude and time. The purpose of this paper is to describe and discuss those long-period variations which have occurred since the beginning of the IGY when stratospheric observations became available from a large number of stations on a regular basis. Of particular interest are those features associated with the biennial or, as it is sometimes called, the '26-month oscillation.'

2. TIME-HEIGHT SECTIONS

In order to provide a detailed account of the behaviour of the zonal wind during this period a series of time-height sections for eight latitudes between 32°N and 20°S (Fig. 1) were prepared. This method of presentation has been employed previously for individual stations by Reed (1961) and Belmont and Dartt (1964). The present study utilizes a fact which was strongly suggested by the similarity between time-height sections for stations at neighbouring latitudes in the studies cited above; namely that the variations in question are basically independent of longitude. Accordingly, monthly mean zonal winds for each latitude belt were computed by averaging together the respective means of the stations in the belt, the station means being weighted by the number of observations which they comprise, as was the case in the companion paper by Wallace and Newell (1966). The number of observations at individual stations varies considerably from month to month and from level to level and hence the values at different points in the time height sections are based on different station distributions. The smoothness of the sections in Fig. 1 despite the heterogeneity of the data is further evidence for the validity of the assumption of zonal symmetry. Only below the 80 mb level and at latitudes above 20° is there any noticeable difference in the means at different stations within a latitude belt. Table 1 lists the stations within each latitude belt.
The gross features of the biennial oscillation, such as its amplitude and phase distribution and its combination with the annual cycle to produce the effects observed in subtropical latitudes, have been well documented in previous works, (Reed (1964a); Belmont and Dartt (1964)) and no attempt is made to reiterate them here. Emphasis is placed upon some of the more subtle features which are evident in the time-height sections presented herein.

(i) The superposition of annual and biennial cycles presents only an approximate description of the zonal wind behaviour in this region. Each individual regime of easterlies or westerlies appears to have its own peculiar characteristics, which are not accidental features of the data sample, but real physical occurrences. For example, the strong easterly regime of 1962-63 and its rapid disappearance during late 1963 are evident in all the sections within 20° of the Equator. Even short-period features cover a wide range of latitude. For example, the double maximum in the westerlies during the 1960-61 Northern Hemisphere winter is discernible as far south as 8°N and the strong westerlies which occurred

![Figure 1](a). Time-height sections of zonal wind averaged around latitude circles as indicated. Solid lines are placed at increments of 10 m sec⁻¹. Shaded areas are westerlies.
prior to the January 1963 warming at high latitudes of the Northern Hemisphere actually appear to extend across the Equator at high levels.

(ii) One feature common to all wind regimes is the tendency for the leading edge of the westerlies to propagate downwards more rapidly than that of the easterlies. In other words, the rate of downward propagation is related to the vertical wind shear. This is best seen close to the Equator where the annual cycle is not present. This difference in propagation rate causes easterly regimes to decrease in vertical extent as they move downwards.

(iii) It appears that the dynamics of the equatorial stratosphere favour the existence of long period wind variations. It is a question of semantics whether these variations, in themselves, constitute a quasi-biennial periodicity. Since it is the opinion of the author that a strict two-year periodicity does, at times, exist in this region, the tendency for alternating easterly and westerly wind regimes will not be regarded, in itself, as a periodicity.

Figure 1 (b). Time-height sections of zonal wind averaged around latitude circles as indicated. Solid lines are placed at increments of 10 m sec$^{-1}$. Shaded areas are westerlies.
TABLE 1. Stations used in zonal averages, grouped together in their respective latitude bands. Asterisks indicate stations which have data available for 3 years or less.

32°N  See Fig. 1 in Wallace and Newell (1966).
14°N Trinidad (11°N, 62°W), Eniwetok (11°N, 162°E), Curacao (12°N, 69°W), San Andres (13°N, 82°W), Guam (14°N, 145°E), Luzon (15°N, 121°F), Guadeloupe (16°N, 62°W), Sal (17°N, 22°W).
8°N Ponape (7°N, 158°E), Majuro (7°N, 171°E), Koror Peleiu (7°N, 134°E), Truk (7°N, 151°E), Kwajalein (9°N, 168°E), Balboa (9°N, 80°W), Yap (10°N, 131°E).
3°S Guayaquil* (2°S, 80°W), Canton Is. (3°S, 172°W), Fernando Noronha (4°S, 32°W).
8°S Ascension Is. (8°S, 14°W), Recife (8°S, 35°W), Luanda* (9°S, 13°E).

As was pointed out in the companion paper, (loc. cit.) prior to 1963 there had been a real two year periodicity in the zonal winds in the Tropics for about a decade. It was further noted that this periodicity was associated with a year to year variation in the intensity of the winter circulations in both hemispheres. Evidence was presented to the effect that the winter circulations have failed to show this periodic behaviour since 1963. It is clear from Fig. 1 that the two year periodicity, as such, is also absent in the zonal winds since 1963. Particularly noticeable are the presence of westerlies at all levels in the Northern Hemisphere sub-Tropics during the 1963-64 winter and the long duration of the last few wind regimes in the Tropics.

Figure 1 (c). Time-height sections of zonal wind averaged around latitude circles as indicated. Solid lines are placed at increments of 10 m sec\(^{-1}\). Shaded areas are westerlies.
3. Meridional cross-sections

In order to present an instantaneous picture of the wind profiles for various configurations of wind regimes a series of meridional cross-sections spanning three years at two month intervals has been prepared, using the same data as in the time-height sections. These are shown in Fig. 2.

This sequence shows that the equatorial wind regimes exist apart from the higher latitude seasonal circulations and maintain their identity as they propagate downwards. The flattening of the easterly regimes due to the different descent rates of the leading edges of easterlies and westerlies is also evident.

4. The momentum budget

The zonally averaged equation governing the balance of westerly momentum may be written as

\[
\begin{aligned}
\frac{\partial [u]}{\partial t} &= - \frac{1}{a \cos^2 \phi} \frac{\partial}{\partial \phi} \cos^2 \phi \left[ u' v' \right] + \left( f - \frac{1}{a} \frac{\partial [u]}{\partial \phi} \right) [v] - \frac{\partial [u]}{\partial z} [w] \\
- 2 \Omega \cos \phi \left[ w \right] - \frac{1}{\rho} \frac{\partial}{\partial z} \rho \left[ u' w' \right]
\end{aligned}
\]

Figure 2 (a). Meridional cross-sections of zonal wind averaged around latitude circles for months indicated. Solid lines are placed at increments of 10 m sec\(^{-1}\). Shaded areas are westerlies.
neglecting variations of density in the horizontal. Here \( a \) and \( \Omega \) are the Earth's radius and angular velocity respectively, \( f = 2\Omega \sin \phi \) is the Coriolis parameter, \( \rho \) is density, \( u, v \) and \( w \) are the zonal, meridional and vertical wind components respectively, \( z \) is the vertical coordinate, \( \phi \) is latitude and \( t \) is time. \( \langle \cdots \rangle \) denotes the zonal average of a quantity, and \( \bar{\cdots} \) the time average.

Before discussing the momentum budget in general it is convenient to assess the importance of the last two terms in the above equation. The fourth term on the right-hand side represents the advection of the Earth's angular momentum by the mean vertical motions. It can be seen by comparing typical magnitudes of the coefficients of \( [\cdots] \) in terms (3) and (4) that this effect is almost two orders smaller than that of the previous term and thus it can be neglected.

Term (5) represents the divergence of the vertical flux of momentum by all scales of eddies and includes frictional effects. Dickinson (1962) has computed the contribution of synoptic scale eddies to this term, using adiabatically computed vertical velocities. It was found that the vertical flux divergences associated with this scale of motion are about half an order of magnitude smaller than the horizontal divergences of term (1), and that the momentum transports are, in general, up-gradient; in Tucker's (1964) formulation this would imply a negative vertical eddy diffusion coefficient for this scale of motion. It is possible that less organized, smaller scale motions might counteract this effect by transporting momentum down the gradient.

There are several difficulties involved in attempting to attribute the observed downward propagation of the wind regimes in the Tropics to a vertical diffusion process:

![Figure 2 (b). Meridional cross-sections of zonal wind averaged around latitude circles for months indicated. Solid lines are placed at increments of 10 m sec⁻¹. Shaded areas are westerlies.](image-url)
(i) Zones of strong vertical wind shear separating easterly and westerly wind regimes can be followed for many months as they move downwards. This is best seen in the section for 3°S in Fig. 1 (b). It will be noticed that the intensity of the wind shear within such a zone (following it as it moves downwards) does not decrease with time until the zone passes below 50 mb. A diffusion process would imply that the wind regimes propagate downwards by a transport of momentum down the gradient with a consequent diminution of the gradient with time. This is evidently not the case above 50 mb, although it may be so at lower levels.

(ii) Measurements of the vertical spread of radioactive debris in the tropical stratosphere by Friend, Feely, Krey, Spar and Walton, (1961), suggest an eddy diffusion coefficient in the order of $10^3 \text{ cm}^2 \text{ sec}^{-1}$. If this value is applied to the diffusion of momentum it is found to be almost an order of magnitude too small to account for the observed zonal accelerations at 50 mb and above.

Thus, with the possible exception of the region below 50 mb it appears reasonable to neglect the role of eddy processes in the vertical exchange of momentum associated with the biennial wind oscillation. With this assumption the right-hand side of the momentum equation reduces to the first three terms. Term (1) represents the horizontal divergence of eddy momentum transports. Reed (1961) has shown that this is the only mechanism capable of introducing westerly momentum into the equatorial region. Similarly it is the only mechanism capable of removing westerly momentum from the tropical region as a whole. It is therefore responsible for all changes in vertically integrated westerly momentum which are symmetric about the Equator. This last condition excludes the annual cycle.

![Figure 2c. Meridional cross-sections of zonal wind averaged around latitude circles for months indicated. Solid lines are placed at increments of 10 m sec$^{-1}$. Shaded areas are westerlies.](image-url)
It is evident from the data presented in the companion paper that this mechanism is most effective at high levels (20 mb and above) where disturbances associated with the polar night vortex of the winter hemisphere often extend into the sub-Tropics. Even these disturbances are only large enough to cause moderate accelerations so that, in effect, the zonal wind in the Tropics responds to the momentum transports which accumulate over a period of months rather than to the individual disturbances themselves. This explains the absence of short-period features in the time-height sections.

It is shown in the companion paper (loc. cit.) how winter to winter differences in the momentum transports at middle latitudes lead to a pattern of alternating convergence and divergence of angular momentum in the tropical stratosphere above 20 mb, which can account for most of the observed changes in zonal wind at those levels.

Although it must be the momentum transports which give rise to the wind regimes in the Tropics, this mechanism cannot explain the propagation of the same regimes into the lower stratosphere, since the observed transports fail to exhibit any year to year differences in the Tropics below 20 mb and there is no evidence of the phase shift in the vertical that is observed in the zonal winds. Thus it appears that some type of mean motion is also necessary to explain the observed wind field.

The second term on the right represents the effects of mean meridional motions. Dickinson (1962) has pointed out that this is the only term which could be large enough to account for the seasonal wind reversals evident in Figs. 1 and 2. He estimated that a mean drift of about 5 cm sec$^{-1}$ from the spring hemisphere into the autumn hemisphere could bring about the observed accelerations. This would amount to a displacement amplitude in the order of a few degrees of latitude over the course of a year.

The effect of mean meridional motions on the biennial wind oscillation is not as obvious. Except at very low latitudes the accelerations involved are generally much smaller than those associated with the annual cycle and mean meridional motions are only one of several possible mechanisms which could account for them. It can safely be said that within a few degrees of the Equator, where the Coriolis parameter and the latitudinal gradients of the zonal wind are both very small, the magnitude of this term is negligible compared with the observed zonal wind accelerations.

Thus it appears that the third term, representing the advection of momentum by mean vertical motions is responsible for the downward propagation of the oscillation at very low latitudes, which is essentially the same result that Tucker (1964) arrived at in his more theoretical formulation. This means that the slopes of the isotachs in the time-height section for 3°S (Fig. 1) should give a good representation of the vertical motion field over the Equator between about 20 and 50 mb. This assumption leads to a mean downward drift of about 0.03 cm sec$^{-1}$. For other latitudes, the rate of downwards propagation of the oscillation can be measured by subtracting out the annual cycle. Reed (1964a) and Belmont and Dartt (1964) have shown that the wind oscillation propagates downwards at essentially the same rate at all latitudes within 20° of the Equator. However, it does not follow that this propagation rate is a measure of the vertical motion field except at the Equator, since mean meridional motions (term 2) are also capable of effecting an exchange of momentum in the vertical.

The fact that at the Equator, the lower edges of the westerly regimes appear to move downwards faster than those of the easterly regimes implies that the mean downward motion is enhanced where the vertical wind shear is positive, and diminished where it is negative. It follows from continuity that the associated meridional motions would be adjusted by this differential descent rate in such a way as to effect a vertical exchange of momentum in the same sense as the vertical motions. For example, if at the Equator westerlies are replacing easterlies at some level, and downward motion is stronger than usual there, then at a slightly higher latitude, the flow is more equatorwards than usual above this level, and more polewards than usual below. Coriolis torques are generating easterlies above and westerlies below, which has the same effect as a downward transport of westerly momentum at the higher latitude. Such a mechanism seems more likely to be responsible for the downward propagation of the oscillation at sub-tropical latitudes than the advection
of momentum by a mean downward drift, since as Tucker (1964) has shown, the mean meridional motions associated with a uniform mean downward drift within 20° of the Equator of the size thus required would be in the order of 50 cm sec⁻¹ at 20°. This would be large enough to wreak havoc with the momentum budget at middle latitudes.

5. The heat budget

The assumption of a mean downward drift at the Equator leads to the notion of a radiative heat sink in that region. Otherwise it would be impossible to account for the fact that the Equator is colder than the sub-Tropics at these levels. Because of uncertainties in solving the radiative transfer equations which are only now being dealt with (see Rodgers and Walshaw (1966)) and the lack of data on the distribution of ozone and water vapour at low latitudes it is difficult either to support or refute this hypothesis from radiative considerations at present. (Only at the tropopause itself can a mean downward motion be ruled out from radiative considerations). Considering that our present understanding of the momentum budget of this region is at least as good as that of the heat budget, it would seem no less direct to infer the vertical motion field from the momentum budget than to infer the meridional motion field from the heat budget as was done by Murgatroyd and Singleton (1961).

A mean downward drift in the order of 0.03 cm sec⁻¹, based on the descent rate of the wind regimes, would lead to a required radiative cooling rate in the order of 0.3°C per day. This is of roughly the same magnitude as that computed by Kennedy (1964) and others, but it is of opposite sign. Further work is required to resolve this contradiction.

The long period motions under consideration are in geostrophic equilibrium to within 1 km of the Equator, and it has been observed that there are temperature fluctuations in the Tropics with amplitudes in the order of 2°C which are associated with the wind fluctuations. Qualitatively speaking, warm temperatures are required in the Tropics relative to the sub-Tropics in the region where the wind shear is positive, i.e., where westerlies are propagating downwards into easterlies. Since the temperature is determined by a balance between radiation and adiabatic heating or cooling due to vertical motion, an increase in downward vertical motion is required in order to maintain a warm temperature in this region against radiative cooling. (If the mean downward motion is large enough to account for the vertical propagation of the wind regimes, the associated heating rate would be more than an order of magnitude larger than the effects of the divergence of eddy heat flux, which was discussed in the companion paper (loc. cit.).) The model proposed by Reed (1964b), which invoked a system of downward propagating mean meridional cells is based on essentially the same physical mechanism. It is difficult to assess the magnitude of the vertical motions thus caused because of the lack of reliable information on radiative time constants. For an order of magnitude estimate, let it be assumed that in the long term mean there is a net downward motion of 0.03 cm sec⁻¹ which is balancing a cooling rate of 0.3°C per day. To maintain a temperature oscillation of 2°C from this mean state against a radiative relaxation time of 20 days this would require a corresponding vertical motion oscillation of about 0.01 cm sec⁻¹, which is consistent with Reed's (1964b) results. Under these conditions, the lower edge of a westerly regime would propagate downwards at approximately twice the speed of that of an easterly regime, and this is approximately what is observed. Thus it seems likely that the peculiar shape of the wind regimes in the time-height plane arises from the requirements of geostrophic equilibrium upon the vertical motion field. Furthermore, as stated in the previous section, the meridional motions arising from the same vertical motion field may be responsible for the broad latitudinal extent of the oscillation.

6. Concluding remarks

While it is impossible with the data available at present to give a detailed account of the momentum and heat budgets of the tropical stratosphere, it is possible at least to form a qualitative notion of the meridional wind field necessary to fulfil both budgets and thus
keep the zonal wind and temperature fields in geostrophic equilibrium. The resulting
meridional wind field is similar to the models of both Reed (1964b) and Tucker (1964); in fact, it is in effect a superposition of the two—a steady descending current over the
Equator modulated by a weaker secondary cell which propagates downwards with the zonal
wind regimes. The fact that the lower edges of westerly regimes are observed to propagate
downwards more rapidly than those of easterly regimes lends support to this hypothesis.

The above model applies equally well whether or not the zonal winds exhibit a two
year periodicity, as can be seen from the time-height sections. The long term variations
in the momentum fluxes, which ultimately give rise to the wind regimes in the Tropics,
appear to govern the periodic nature of the phenomenon; i.e., if the fluxes are periodic,
then the zonal winds will be periodic. It remains to be seen whether the zonal winds, in
turn, exert any influence on the momentum transports. Such a feedback mechanism might
explain the quasi-periodic nature of the phenomenon.

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