Kelvin Waves in the Equatorial Middle Atmosphere Observed by the Nimbus 5 SCR

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ABSTRACT

The structure and behavior of Kelvin waves in the equatorial upper stratosphere and mesosphere are investigated by the use of infrared radiation measurements from the Selective Chopper Radiometer (SCR) on the Nimbus 5 satellite during the two years 1973–74.

By making a combination of three upper channels of the SCR, Kelvin waves with vertical wavelengths of ~20 km are detected in the tropics. The long-term statistics indicate that zonal wavenumber 1 is prominent throughout the two-year period. The predominant period of the wave is determined by power spectrum analysis using the Doppler effect due to the wave migration. For wavenumber 1, the eastward moving Kelvin wave appears to have a period of 4–9 days. It is also found that the intrinsic (Doppler-shifted) phase velocity of the Kelvin wave is almost constant in time, regardless of the seasonal variation of the mean zonal wind.

The dynamical significance of this wave is stressed in connection with the semiannual oscillation of the mean zonal wind in the equatorial middle atmosphere.

1. Introduction

In the last decade it has been well known that large-scale equatorial waves play an essential role in producing long-term variations of the mean zonal wind such as those associated with the quasi-biennial oscillation (QBO) in the tropical lower stratosphere. Observational and theoretical aspects of this phenomenon are summarized by Wallace (1973) and Holton (1975).

Regarding the semiannual oscillation of the mean zonal flow in the equatorial upper stratosphere and lower mesosphere, however, there still remains a question as to the nature of waves which supply momentum for the mean zonal wind acceleration. In our previous study (Hirota, 1978, hereafter designated as HA), an attempt was made to find evidence of the predominance of Kelvin waves over the height interval between 25 and 60 km from a power spectral analysis of wind and temperature based on meteorological rocket observations at Ascension Island. It was shown by HA that the wave has a characteristic vertical scale of about 20 km and a period $\leqslant 10$ days. Since the Kelvin wave has the property of transporting westerly momentum vertically, it is suggested that the semiannual cycle in mean zonal wind could be accounted for in a similar way as shown by Lindzen and Holton (1968) and Holton and Lindzen (1972) for the QBO.

Recently, using the parameters of the Kelvin wave found by HA together with the thermal damping rates of Dickinson (1973) and Blake and Lindzen (1973), Dunkerton (1979) made a numerical model for the westerly accelerations of the semiannual oscillation and demonstrated that such a Kelvin wave could indeed give rise to the observed accelerations.

It should be noted, however, that the period of zonal wind oscillations strongly depends on the assumed phase velocity and wavenumber of the waves as well as on the incident momentum flux and the thermal damping rate, as was shown theoretically by Plumb (1977). The phase velocity of the Kelvin wave given by HA is merely an estimate based on the observed value of the vertical wavelength with an assumed zonal wavenumber, since no direct information about them can be obtained from an analysis based on single-station observations.

Therefore it is desirable at this stage to make more detailed observational studies of Kelvin waves in order to obtain a deeper insight into the nature of the semiannual variation of the mean zonal wind in the equatorial middle atmosphere. Thus, the main purpose of the present study is to determine the dominant wavenumber and phase velocity of Kelvin waves directly from global satellite observations and to describe their seasonal variations in terms of the semiannual cycle.

2. The Nimbus 5 SCR and waves

The Nimbus 5 Selective Chopper Radiometer (SCR) radiance data supplied by the Department of Atmospheric Physics of the University of Oxford are used in the present study.

Although there have been many observational

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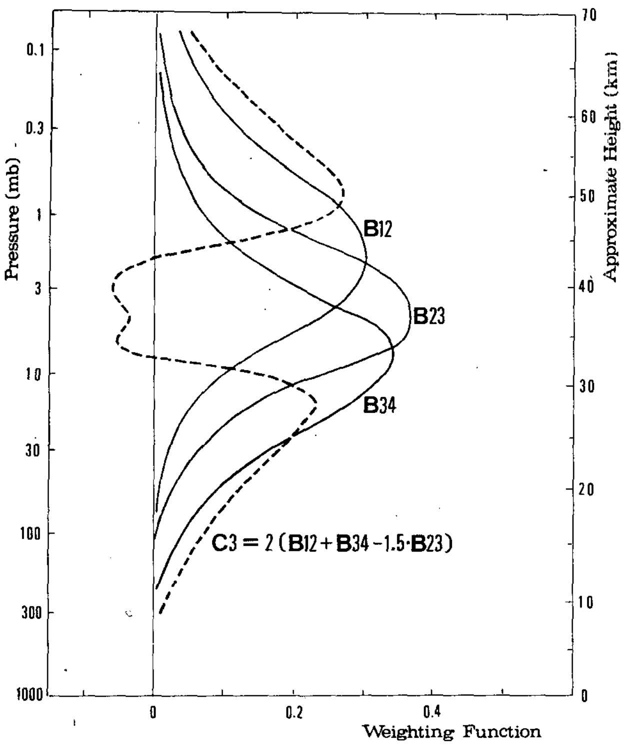

FIG. 1. The weighting functions of the Nimbus 5 Selective Chopper Radiometer.

studies using the SCR data to describe large-scale wave disturbances in the stratosphere, most of them confined their discussions to planetary Rossby waves in middle and higher latitudes, which have characteristic vertical scales long enough to be easily detected by single-channel observations.

Regarding planetary waves in the tropics, Barnett (1975) and Hirota (1976, hereafter designated as HB) have shown, with the aid of SCR top-channel data, that midlatitude Rossby waves penetrate into the equatorial upper stratosphere in the westerly phase of the mean zonal wind. As is clearly shown in Figs. 7 and 8 of HB, such a Rossby wave in the tropical stratosphere has a tendency to travel westward, whereas no eastward moving wave has been found so far from single-channel SCR data.[1]

In view of a fact that the vertical wavelength of the Kelvin wave found by HA is of order 20 km, it would be difficult to detect such a short vertical scale wave from the SCR data of single channels which have a broad weighting function in the vertical. Therefore, it is necessary to devise a new scheme for the Kelvin wave analysis using several SCR channels.

3. A new channel of the SCR

For the purpose of detecting short vertical scale waves, a new channel is designed by making a combination of three upper channels of the SCR of the form

$$C3 = 2(B12 + B34 - 1.5\,B23),$$

where B12, B23 and B34 are the original channels of the Nimbus 5 SCR and the factor 2 is for normalization.

Fig. 1 shows the vertical distribution of the weighting functions of these channels. The weighting function of the new channel C3 has two maxima at ~30 and 50 km and a minimum at ~40 km so as to fit a wave with a vertical scale of the order of 20–30 km. It should be noted that the wave under consideration would be predominant in the height region between 20 and 60 km corresponding with the appearance of the semiannual zonal wind oscillation centered at the stratopause (see Fig. 2 of HA).

The response of these channels to temperature waves with various vertical wavelengths and a constant unit amplitude is illustrated in Fig. 2. The response characteristics of B23 and B34 are almost the same as that of B12, so they are not shown here. Note that the response to a wave with infinite vertical wavelength must be unity, because the weighting function of each channel is normalized.

It can be seen from Fig. 2 that the response of the original SCR channels (B12, B23, B34) increases gradually with increasing vertical wavelength, while the new channel C3 has a maximum response to waves with wavelengths of the order of 30 km and a minimum to those with wavelengths of ~60 km. As a result, the response of C3 is about three times larger than those of the B's for wavelengths of 20 to 30 km. Therefore it can be said that the new channel designed here is a good amplifier for the Kelvin waves under consideration

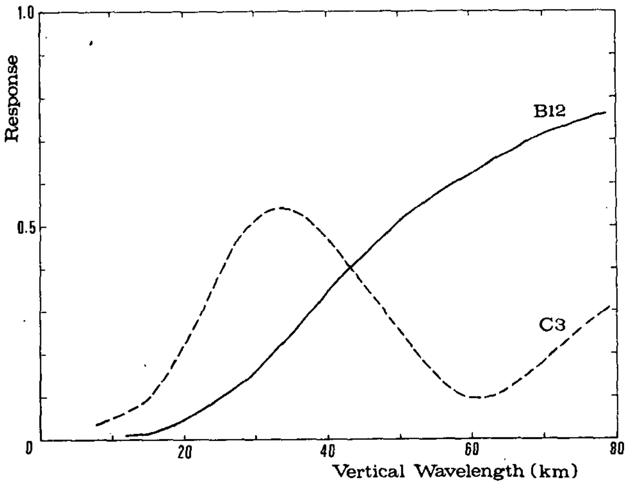

FIG. 2. The response of the Nimbus 5 SCR channels B12 and C3 to the temperature wave of unit amplitude with various vertical wavelengths.

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[1] Webster *et al.* (1977, unpublished work) have revealed fragmentary evidence of temperature fluctuations with a time scale near 7–8 days in the tropical stratosphere, using channel B23 data from the SCR, and suggested the possibility of Kelvin waves. No further analysis was made, however.

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which are not effectively observed by the original SCR channels.

4. Results of the wave analysis

In order to see the behavior of planetary-scale waves in the equatorial middle atmosphere, a harmonic analysis is made of radiance temperature waves on daily basis during the two years from January 1973 to December 1974, mainly with the use of grid-point data (every 10° in longitude and every 4° in latitude) of C3 and B12. Values at three latitudes (4°N, equator, 4°S) are averaged with weights of 1/4, 1/2 and 1/4, respectively, as representative of the equatorial region.

a. Long-term statistics

Since the amplitude and phase angle vary from day to day, we will first consider the long-term statistics on wave amplitude in order to survey the wave activity throughout the period of analysis.

Two types of averages are defined as a function of zonal wavenumber and channel: one is the root mean square of daily amplitude, designated as $\langle A \rangle$, and the other is the mean amplitude of 20-day averaged field, denoted by $\bar{A}$. In the latter, the length of the average duration is chosen by recalling the fact that the wave period is of order 10 days. Notice that $\bar{A}$ is therefore considered to be roughly a measure of the stationary wave activity.

The magnitude of each wave over the two-year period is summarized in Fig. 3. The unit of wave amplitude is the radiance unit [mW m^{-2} $ster^{-1}$ $(cm^{-1})^{-1}$], which is approximately equal to K.

From this figure we can see the following:

1) For both $\langle A \rangle$ and $\bar{A}$, the mean amplitude is largest for wavenumber 1 and decreases with increasing wavenumber.

2) For low wavenumbers, the ratio $\langle A \rangle / \bar{A}$ is about 2 for waves observed by B12, while it is larger than 3 for C3. This means that the wave observed by C3 includes a relatively large amount of transient (traveling) components.

3) The rms daily amplitude $\langle A \rangle$ of C3 is two to three times larger than that of B12 for low wavenumbers. In view of the response character shown in Fig. 2, this must be an indication of the predominance of waves with a vertical scale of about 20–30 km. It is also suggested, from the filter response of C3, that the wave amplitude of wavenumber 1 is about 3–5 K on the average.

For wavenumbers >4, the wave amplitude is considered to be nearly equal to the instrument noise level. Since channel C3 consists of the combination of three channels with coefficients 2, 3 and 2, random errors of C3 must be enlarged by a factor $(2^2+3^2+2^2)^{\frac{1}{2}}=4.12$. In this respect, it is noteworthy that the amplitude of C3 is about four times larger than that of B12 for high wavenumbers for both $\langle A \rangle$ and $\bar{A}$. Therefore it can be concluded from Fig. 3 that the wave amplitude of low wavenumbers is significantly above the noise level.

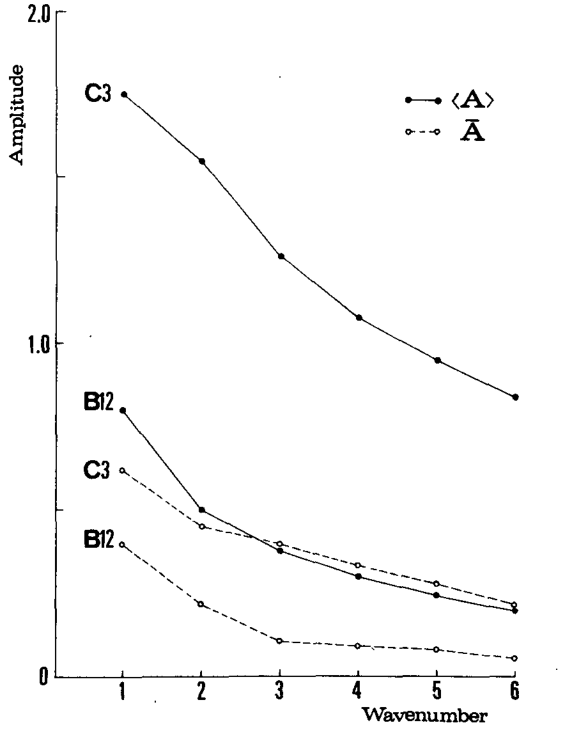

FIG. 3. Spectral distribution of wave amplitudes observed by B12 and C3 at the equator for the period 1973–74.

b. Time-longitude section analysis

In order to see the day-to-day fluctuations of the temperature field over the equator, a simple time-longitude section is made of channel C3 radiance for the first 50 days of 1973 (Fig. 4), where the zonal mean is removed on daily basis.

Roughly speaking, there appear large-scale traveling disturbances with a time scale of order 10 days. The time variation of the wave intensity appearing in this figure suggests that both the eastward and westward moving components, corresponding to Kelvin waves and Rossby type waves, are included.

The tendency of the wave migration may be seen more clearly if a sort of filtering in space and time is applied to these data.

c. Determination of the Kelvin wave period

An attempt is now made to directly determine the period (or phase velocity) of Kelvin waves by using a power spectral estimate in space and time with the aid of the Doppler effect due to the wave migration. The method of analysis used here is almost the same as that given by HB for describing the seasonal variation of

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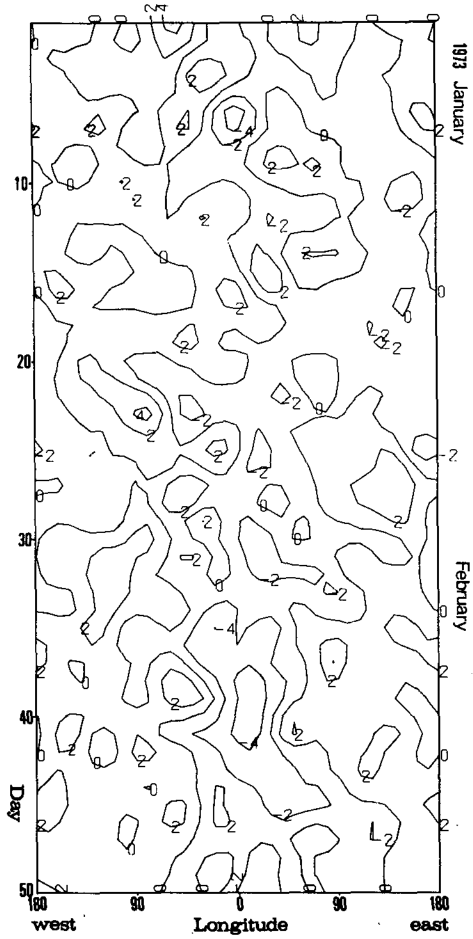

FIG. 4. Time-longitude section of the channel C3 radiance along the equator. Zonal mean is removed.

transient planetary Rossby waves in the upper stratosphere. Computations are made every 20 days for wavenumbers 1 and 2 of the channel C3.

Fig. 5 shows a result of such a spectral analysis for wavenumber 1 over the equator for the two-year period 1973–74. Inspection of this figure reveals that 1) there appear to be two types of traveling waves predominating throughout the two-year period as denoted by heavy broken lines: one is an eastward moving mode with a period of 4 to 9 days, and the other is a westward moving mode with a period of one to three weeks; 2) as regards the eastward moving wave, roughly speaking, the dominant period shows a semiannual cycle with period maxima occurring in January and July and period minima in March and September; 3) due to the semiannual zonal wind variation, denoted by a thin broken line which corresponds to the climatological value at 50 km over the equator as determined by Belmont *et al.* (1975), the intrinsic (Doppler-shifted) phase velocity of the eastward moving wave is almost constant with season (60–80 m s^{-1} at this level), despite the wide range of the ground-based phase velocity (50–110 m s^{-1}); 4) the power spectral density, which is a measure of the wave amplitude, of the eastward moving wave does not show an apparent semiannual cycle.

From the discussion so far it can be concluded that the eastward moving wave appearing in Fig. 5 is the Kelvin wave, while the westward traveling one is identified as the Rossby wave since it behaves in a similar manner to that of the wave observed by the channel B12 (cf. Figs. 7 and 8 of HB). It is also noteworthy, though not shown here, that the result of computation for wavenumber 1 at 8° latitude (average of 8°N and 8°S) shows the eastward moving wave similar to that of Fig. 5 but with weaker magnitude. This supports the interpretation of this feature as an equatorially trapped Kelvin wave.

Wavenumber 2, on the other hand, indicates no such systematic concentration of power spectral density into narrow bands of period as in the case of wavenumber 1, in spite of the comparable magnitude of wave amplitude as denoted in Fig. 3.

5. Discussion

As an extension of our previous works (HA and HB), the predominance of the Kelvin wave of wavenumber 1 in the equatorial middle atmosphere has been proved from the power spectral analysis of the Nimbus 5 SCR data. Finally, a more detailed discussion is made of some characteristic properties of the wave by comparing with former observations and theories.

Generally speaking, the vertical wavelength L of Kelvin waves is given by

$$L=2\pi\hat{c}/N,$$

where $\hat{c}$ is the Doppler-shifted phase velocity and N the buoyancy frequency (Holton, 1972).

Using the observed value of $\hat{c}=60$–80 m s^{-1} at the 50 km level and assuming $N=2.2\times10^{-2}$ s^{-1} for the upper stratosphere, we obtain $L=17$–23 km. Due to the vertical shear of the mean zonal wind, $\hat{c}$ would become somewhat larger with decreasing height, say, 70–90 m s^{-1} at ~40 km, which in turn gives $L=20$–26 km. Anyway it is interesting to note that the vertical wavelength L thus estimated is very close to the one observed by HA. This also assures the validity of the use of channel C3 for detecting such a Kelvin wave.

The Kelvin wave amplitude, which is averaged over a deep layer between 20 and 60 km, can be evaluated by integrating the power spectral density over a period range of several days centered at the peak value. Disregarding the seasonal variation of the wave activity, the amplitude is found to be near 4–6 K, which is also close to the estimate of HA.

As was mentioned earlier, the phase velocity of Kelvin waves is one of the most important factors in explaining the observed features of the semiannual oscillation of mean zonal wind in the tropical middle atmosphere. In his numerical calculation of the wave-

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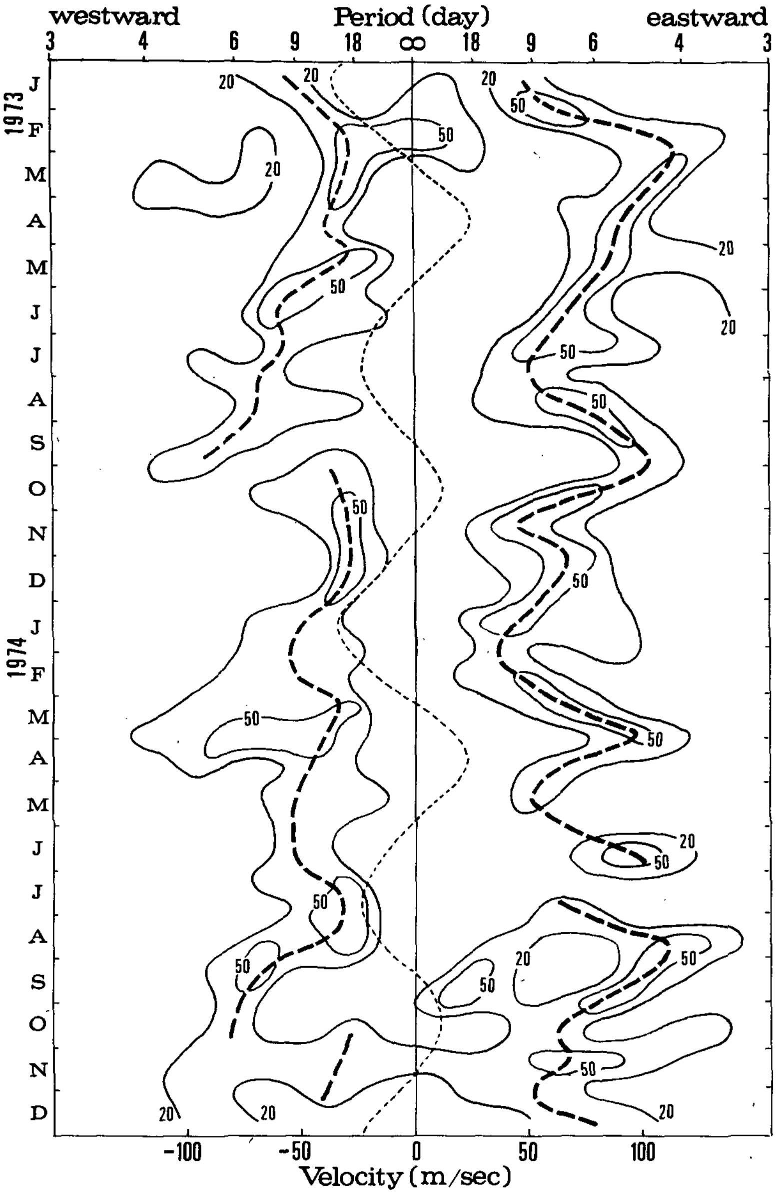

FIG. 5. Seasonal variation of the power spectral density of radiance temperature waves of wavenumber 1 observed by C3 over the equator. Thin dashed line denotes the climatology of the mean zonal wind over the equator at 50 km height.

induced zonal flow acceleration, Dunkerton (1979) demonstrated that the most reasonable values of the ground-based phase velocity c appear to lie in the range $45 \leqslant c \leqslant 60$ m s^{-1} for wavenumber 1, when the thermal damping rate of Dickinson (1973) is assumed. In this respect, it is quite interesting to note that such a slow phase velocity is indeed found by the present analysis (Fig. 5) in January–February and July–August in coincidence with the stage of westerly accelerations of the mean zonal wind. Therefore, it seems very likely that the Kelvin wave observed in this study plays an essential role in producing the mean westerly flow in the semiannual oscillation.

The characteristics of this Kelvin wave, however, are representative of a deep layer including the stratosphere and mesosphere, because of the wide range of the channel C3 weighting function. The vertical distribution of the wave amplitude and phase, for example, cannot be given by the present method of analysis. Further observational studies are therefore required to increase the vertical resolution. Measurements from the Nimbus 7 Stratosphere and Mesosphere Sounder (SAMS) and Limb Infrared Monitor of the Stratosphere (LIMS) would be of great importance in this regard.

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REFERENCES

Barnett, J. J., 1975: Hemispheric coupling—Evidence of a cross-equatorial planetary waveguide in the stratosphere. *Quart. J. Roy. Meteor. Soc.*, **101**, 835–845.

Belmont, A. D., D. G. Dartt and G. N. Nastrom, 1975: Variation of stratospheric zonal winds, 20–65 km, 1961–1971. *J. Appl. Meteor.*, **14**, 585–594.

Blake, D., and R. S. Lindzen, 1973: The effect of photochemical models on calculated equilibria and cooling rates in the stratosphere. *Mon. Wea. Rev.*, **101**, 783–802.

Dickinson, R. E., 1973: Method of parameterization for infrared cooling between altitudes of 30 and 70 kilometers. *J. Geophys. Res.*, **78**, 4451–4457.

Dunkerton, T., 1979: On the role of the Kelvin wave in the westerly phase of the semiannual zonal wind oscillation. *J. Atmos. Sci.*, **36**, 32–41.

Hirota, I., 1976: Seasonal variation of planetary waves in the stratosphere observed by the Nimbus 5 SCR. *Quart. J. Roy. Meteor. Soc.*, **102**, 757–770.

——, 1978: Equatorial waves in the upper stratosphere and mesosphere in relation to the semiannual oscillation of the zonal wind. *J. Atmos. Sci.*, **35**, 714–722.

Holton, J. R., 1972: *An Introduction to Dynamic Meteorology.* Academic Press, 319 pp.

——, 1975: *The Dynamic Meteorology of the Stratosphere and Mesosphere. Meteor. Monogr.*, No. 37, Amer. Meteor. Soc., 216 pp.

——, and R. S. Lindzen, 1972: An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080.

Lindzen, R. S., and J. R. Holton, 1968: A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107.

Plumb, R. A., 1977: The interaction of two internal waves with the mean flow: Implications for the theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **34**, 1847–1858.

Wallace, J. M., 1973: General circulation of the tropical lower stratosphere. *Rev. Geophys. Space Phys.*, **11**, 191–222.

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