Theory of the Mesopause Semiannual Oscillation

TIMOTHY J. DUNKERTON[1]

National Center for Atmospheric Research,[2] Boulder, CO 80307

(Manuscript received 3 May 1982, in final form 2 August 1982)

ABSTRACT

A semiannual oscillation in monthly mean wind has been observed in the upper mesosphere over Ascension Island (8°S) and Kwajalein (9°N). It is suggested that the selective transmission of gravity and Kelvin waves through the lower-level stratopause semiannual oscillation is responsible for this "mesopause" semiannual oscillation. No *in situ* semiannual forcing is required at the mesopause.

The theoretical model developed here also illustrates the importance of the time-mean component of the mean zonal flow as it affects wave propagation through the equatorial middle atmosphere.

1. Introduction

In recent years a limited amount of observational evidence has become available suggesting the existence of a semiannual mean zonal wind oscillation in the equatorial upper mesosphere and lower thermosphere (Hirota, 1978; Hamilton, 1982). Rocketsonde mean monthly winds at Ascension Island (8°S) analyzed by Hirota (1978) displayed two notable features of this oscillation. First, as shown in Fig. 1a, the phase of this "mesopause" semiannual oscillation is opposite to that of the "stratopause" semiannual oscillation below. Secondly, Fig. 1b indicates that the two oscillations have rather distinct amplitude maxima approximately centered at the stratopause and mesopause. Maximum semiannual westerlies are observed at the stratopause in April and May, whereas these westerlies appear at the mesopause approximately three months earlier.

Because the time-mean has been removed from Fig. 1a, there is some question whether or not westerlies, *in an absolute sense*, actually appear in either oscillation. This is a dynamically important question for several reasons, one of which is that equatorial westerlies are in super-rotation and cannot be advected into the region unless the atmosphere's angular momentum is in super-rotation relative to the equator (which does not appear to be the case). It is also important to know the absolute mean wind for numerical modeling purposes. I. Hirota (personal communication, 1982) provided the "raw" monthly mean data for Ascension Island in this same time period. As shown in Fig. 2, there appears to be a significant time-mean component throughout the mesosphere. Below 70 km, where the semiannual oscillation is weakest, time-mean westerlies appear to exist. On the other hand, time-mean easterlies are evident above ~75 km; this causes the easterly phase of the mesopause semiannual oscillation to be much stronger than the westerly phase. The westerly phase may, in fact, be very weak, as around December 1970, but it is difficult to say that this is always the case, given such a limited record.

Remarkably, Hamilton (1982) has shown that a very similar semiannual oscillation exists in the mesosphere over Kwajalein (9°N). Figs. 3a,b, taken from Hamilton's paper, show a similar westerly (easterly) time-mean structure in the lower (upper) mesosphere, together with a slightly weaker semiannual oscillation overall. It is of interest to note that the stratopause oscillation appears strongest just south of the equator (Hirota, 1980).

2. Explanation of the mean zonal wind structure

In this paper it will be suggested that the stratopause and mesopause oscillations are dynamically related in the sense that the former is essential to the existence of the latter. In theory, gravity waves of easterly and westerly phase speed will be selectively transmitted through the westerly and easterly phases of the stratopause oscillation, respectively, leading to a semiannually-varying deposition of momentum at upper levels.[3] This idea, which is an extension of concepts put forth by Lindzen (1981) to explain the mean wind structure in the extratropical upper atmosphere,

[1] Current affiliation: Physical Dynamics, P.O. Box 3027, Bellevue, WA 98009.

[2] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

[3] Kelvin waves are a special kind of westerly gravity wave, implicitly included in this remark. With suitable modifications, all equatorially-trapped, vertically-propagating waves could be included within the context of a selective transmission theory.

0022-4928/82/122681-10$06.50

© 1982 American Meteorological Society

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

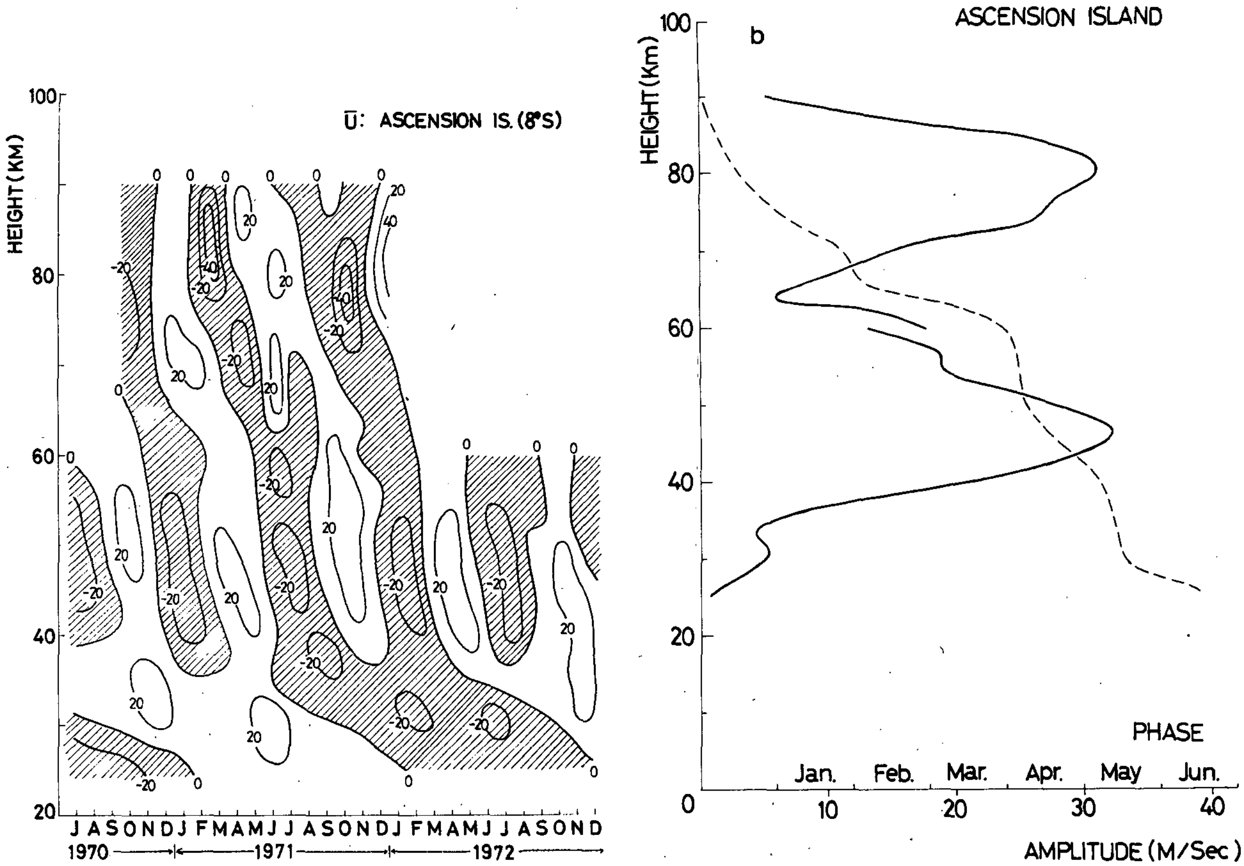

FIG. 1. The semiannual oscillation at Ascension Island (8°S). (a) Oscillation with time-mean and annual cycle removed; (b) amplitude of a sinusoidal fit, and phase of maximum westerlies. From Hirota (1978).

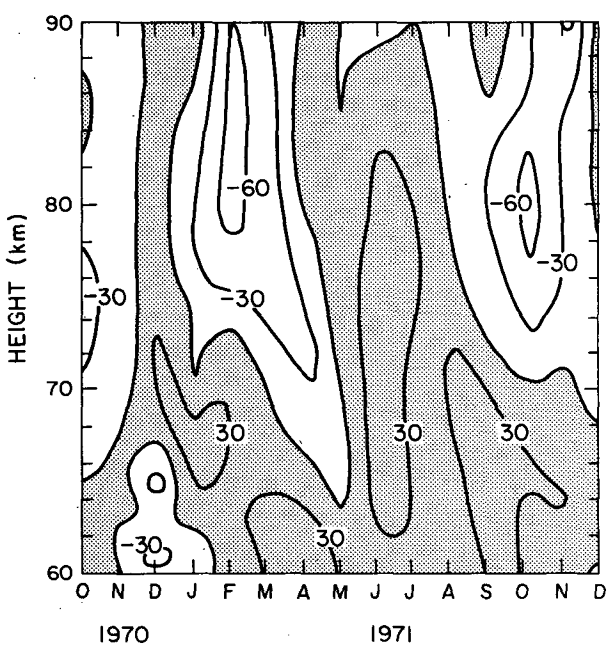

FIG. 2. "Raw" monthly mean winds at Ascension Island for the time period shown in Fig. 1.

was recently examined by the author (Dunkerton, 1982b) in the context of a simplified transient wave model. Fig. 4, taken from that paper, shows an example of the mean flow evolution in this one-dimensional model. The model included: 1) an explicit forcing of a symmetrical quasi-biennial type oscillation in the lower stratosphere (Holton and Lindzen, 1972; Plumb, 1977; Plumb and McEwan, 1978); 2) a prespecified stratopause semiannual oscillation (Holton and Lindzen, 1972); 3) momentum deposition in the mesosphere and lower thermosphere due to easterly and westerly gravity waves; and 4) diffusion and deceleration due to the breaking diurnal tide above 85 km (Lindzen, 1981). The latter were taken to be

$$\nu(z) = \begin{cases} 200 \exp \dfrac{z-85}{7} + 0.3 \text{ m}^2 \text{ s}^{-1}, & z \leqslant 85 \text{ km} \\ 200.3 \text{ m}^2 \text{ s}^{-1}, & z > 85 \text{ km} \end{cases} \tag{2.1}$$

$$\bar{u}_t = -16 \text{ m s}^{-1} \text{ day}^{-1}, \qquad z \geqslant 85 \text{ km}, \tag{2.2}$$

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

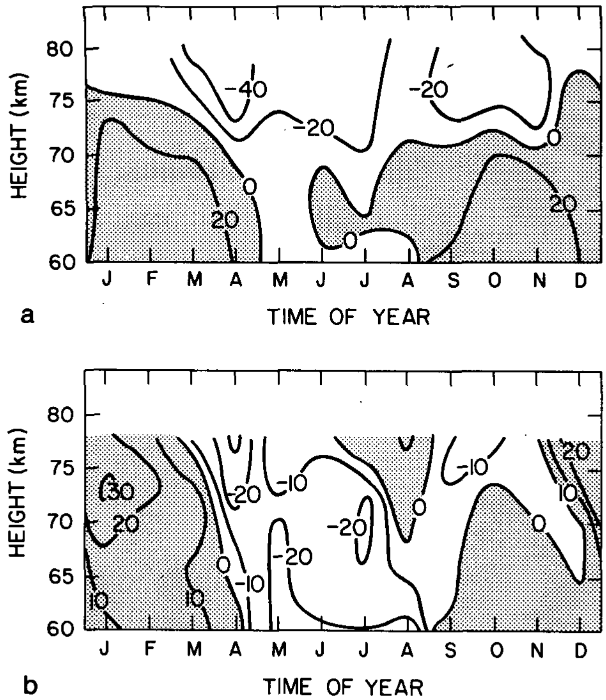

FIG. 3. The mesospheric semiannual oscillation at Kwajalein (9°N), (a) with, and (b) without time-mean and annual cycle. From Hamilton (1982).

as partly suggested by Lindzen (1981). In this model, gravity waves of phase speed $c = \pm 25$ m s^{-1} were allowed to propagate vertically through the low-level flow; momentum deposition was determined for each wave at each time step with the simple formulas

$$\int_{z_f}^{z_c} \rho_0(c - \bar{u})dz \equiv \Delta M, \qquad (2.3)$$

$$\bar{u} \rightarrow c \quad \text{in} \quad (z_f, z_c), \qquad (2.4)$$

where z_c is the critical level where $\bar{u} = c$, $\rho_0 = \exp(-z/H)$, ΔM is the day-integrated momentum flux at the lower boundary, and z_f is the asymptotic height of the trailing shock in the nonsaturated mean zonal wind solution in Dunkerton's (1982a) analytical model. At each time step, i.e., one day, the mean zonal wind was adjusted according to (2.4), with ΔM being determined at each time step in a stochastic manner as

$$|\Delta M| = -33 \text{ m}^2 \text{ s}^{-1} \ln(1 - x), \qquad (2.5)$$

where x is a pseudo-random number on the interval (0, 1). The details of this modeling approach are given in Dunkerton (1982b). Model output shown in Fig. 4 was smoothed with a monthly running mean.

The choice of gravity wave parameters for this model was not arbitrary; it was necessary, for example, to employ phase speeds lying in the range

$$|\bar{u}_{QBO}| < |c| < |\bar{u}_{SSO}|, \qquad (2.6)$$

where $|\bar{u}_{QBO}|$ and $|\bar{u}_{SSO}|$ are the amplitudes of the quasi-biennial and stratopause semiannual oscillations, respectively. Also, the momentum fluxes had to be chosen to generate a mean wind reversal at the proper height.

On the basis of this experiment it was thought that the gravity wave mechanism might provide one plausible explanation of the mesopause semiannual oscillation. Furthermore, the diurnal tidal wavebreaking (Lindzen, 1981) would seem to explain, at least in part, the observed time-mean easterly flow above the mesopause. It is important to note, incidentally, that diffusion due to the tide would remove most of the momentum due to (2.2), but there is nevertheless a residual deceleration which, over a period of 90 days, can produce a strong, and possibly barotropically unstable, easterly jet above the mesopause.

In many respects, Fig. 4 agrees with the Ascension Island data in Fig. 1a. There is, however, a crucial aspect left untreated in this model simulation, *viz.*, the observed time-mean flow below 70 km. As we have seen, there is clearly a time-mean westerly flow in the lower mesosphere. Furthermore, Belmont *et al.* (1974) have given some evidence of a time-mean easterly flow of order -15 m s^{-1} in the equatorial stratosphere. The absence of this time-mean flow in Fig. 4 is due to the fact that the stratopause semiannual oscillation has not been calculated explicitly.

A theory of the stratopause semiannual oscillation was advanced by Dunkerton (1979). The appearance

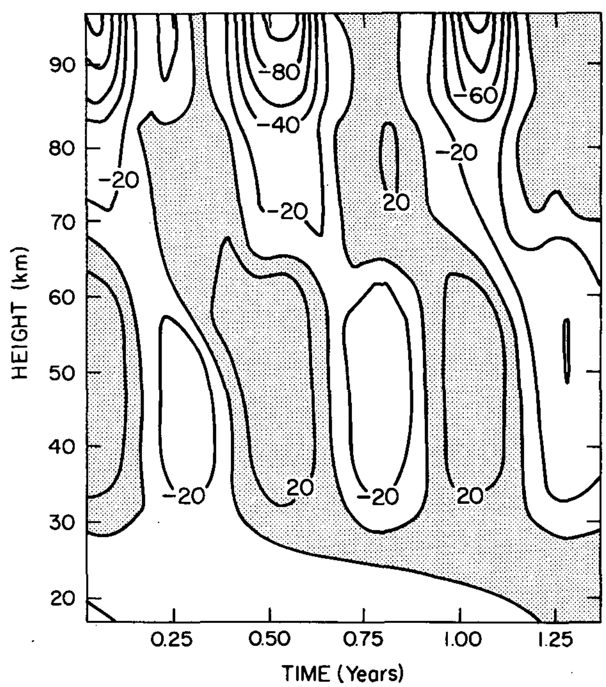

FIG. 4. Model simulation of selective gravity wave transmission in the equatorial middle atmosphere, according to the simplified transient, conservative waves model of Dunkerton (1982b).

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

of absolute westerlies in the lower mesosphere could be attributed to a long vertical wavelength Kelvin wave (Hirota, 1978). The semiannual period of the oscillation, on the other hand, is probably due to the combined effects of horizontal advection $\bar{v}\bar{u}_y$ and planetary wave critical level interaction. The relative importance of these easterly forcings is not known, but an experiment by Holton and Wehrbein (1980) suggested that horizontal advection by itself might provide an adequate semiannual easterly deceleration of the mean flow.

While the upper boundary in Dunkerton's (1979) model was placed at 70 km, it seems reasonably clear that the time-mean westerly flow in the lower mesosphere could be attributed to the Kelvin wave, while the time-mean easterly flow in the stratosphere could be attributed to the easterly forcings there. In other words, the *same* processes which generate the stratopause oscillation seem to explain the observed time-mean structure as well.

Presumably, the semiannual advection easterly forcing decays above the stratopause (Holton and Wehrbein, 1980). Thus the stratopause semiannual oscillation should also decay with height above this level. In retrospect, the observation of this amplitude decrease (Fig. 1b) might constitute *a proof* that the advection easterly forcing decreases with height in this manner.

What remains, then, is to simulate both stratopause and mesopause oscillations simultaneously. It is the purpose of this paper to do just that. This problem is not a trivial one; the reason is that gravity and Kelvin wave propagation depends on the *absolute* mean zonal wind. As a very mild rebuke to some observers, we are not primarily interested in equatorial mean flow oscillations which have time-mean and annual cycles, etc., removed. Such filtering procedures, of course, lead to the most pleasing figures, but are actually *more* difficult to interpret theoretically.

In the next section the numerical model is discussed in detail. In Section 4, we first present a model simulation without the small-scale gravity waves to get some idea of the basic state mean wind profiles into which the gravity waves will be allowed to propagate. This information is then used to ascertain the relevant parameters for the other gravity and Kelvin waves, which might be of importance in the mesopause semiannual oscillation.

After submission of this manuscript, a paper by Salby *et al.* (1982) appeared, claiming to have found both the Hirota Kelvin wave and an additional extreme high phase speed Kelvin wave in LIMS data. Because the latter wave implies a possible additional source of westerly momentum in the equatorial upper mesosphere, it may be important in the mesopause semiannual oscillation.

In fact, our model results suggest that both Kelvin waves could contribute to this oscillation's westerly acceleration phase. However, the effect of these waves seems to depend on an easterly wave propagating from below, or at least an easterly momentum deposition in the upper mesosphere, which "prepares the way" for the westerly waves by enhancing their subsequent vertical propagation.

This easterly forcing would appear to be distinct from the diurnal tide, because the latter experiences unstable breakdown above the mesopause according to Lindzen (1981). There are other possible candidates for the required easterly forcing, such as planetary wave critical layer interaction and the upward propagation of easterly gravity waves. We have chosen to investigate the possible role of the upward propagation in the mesopause semiannual oscillation following Holton (1982) and Matsuno (1982). These studies were directed at the extratropical problem, and both found a tendency for lower thermospheric winds to be reduced or reversed from the lower-level flow, due to the selective transmission of gravity waves. We find that a similar argument directed at the equatorial problem leads to the generation of a mesopause semiannual oscillation approximately out of phase with the stratopause oscillation.

This study does not exclude the possible role of planetary wave critical layer interaction; indeed, Hirota (1978) gave some evidence of semiannually varying planetary wave activity at these heights. The easterly phase descent shown in Fig. 2 is, at first sight, suggestive of the absorption of *vertically-propagating* waves. However, a recent study by the author (Dunkerton, 1982c) suggests that descending easterly shear zones can be induced by *horizontal* fluxes of momentum, provided that the opposite (i.e., westerly) phase is due to vertically-propagating waves.

Needless to say, any gravity and Kelvin wave theory of the mesopause oscillation should be regarded as tentative. It remains to be shown whether these waves actually exist in adequate amounts in the equatorial upper atmosphere, and whether their phase speeds and momentum deposition agrees with this theoretical model. The following material will hopefully provide a stimulus for the placement of an MST radar in the tropical region.

3. Numerical model

In the stratosphere and lower mesosphere this model is essentially that of Dunkerton (1979). The latitudinally-integrated mean zonal flow is governed by the equation

$$\bar{u}_t + \sum_i \frac{1}{\rho_0}(\rho_0 B_i)_z = \frac{1}{\rho_0}\frac{\partial}{\partial z}\rho_0\nu\frac{\partial \bar{u}}{\partial z} + G(z, t), \quad (3.1)$$

where $G(z, t)$ represents the various prescribed forcings and B_i are the wave action fluxes

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

$$B_i = B_i(17)\exp\left[\frac{z}{H} - \int_{17}^{z} D_i(z')dz'\right], \quad (3.2)$$

where z is in km, and D_i the dissipation rates (m^{-1}) dependent on the wave parameters and type. Three equatorial waves are included in the basic state simulation; a Kelvin (KQ) and Rossby-gravity (RG) wave drive the westerly and easterly phases of the quasi-biennial oscillation, respectively (Wallace, 1973; Holton, 1975; and references therein). A second Kelvin wave (KS) generates westerlies around the stratopause (Hirota, 1978). For the Kelvin waves

$$D = \frac{\alpha N}{k(c-\bar{u})^2} + \frac{2\nu N^3}{k(c-\bar{u})^4}, \quad (3.3a)$$

where α is the radiative damping rate, N the static stability, and k the zonal wavenumber. The viscous diffusion term is retained only for the KS wave in view of its possibly high vertical propagation. For the Rossby-gravity wave

$$D_{RG} = \frac{\alpha N}{k_{RG}(c_{RG}-\bar{u})^2}\left\{\frac{\beta}{k_{RG}{}^2(\bar{u}-c_{RG})} - 1\right\}, \quad (3.3b)$$

where β is the planetary vorticity gradient. This formula is applied only up to some evanescent point where the bracketed term vanishes.

The radiative damping rate is crucial to the wave dissipation, obviously, and must be chosen with care. The profile adopted here is

$$\alpha(z) = (12\ \text{days})^{-1}\left\{1.4 + \tanh\frac{z-40}{10}\right\}, \quad (3.4)$$

varying from a 30-day time scale at the tropopause (Holton and Lindzen, 1972) to five days at the mesopause (Wehrbein and Leovy, 1982). The increase in this rate due to the vertical disturbance scale decrease (Fels, 1982) is not modeled here; instead, the five-day figure was chosen as representative for the Kelvin wave in question of which the vertical wavelength is of order 20 km (Hirota, 1978; Wehrbein and Leovy, 1982). It might be of interest, however, to incorporate such an effect explicitly, as Hamilton (1981) has done with regard to the quasi-biennial oscillation.

The formula (3.2) assumes steady waves; while it has been shown that wave transience is chronologically important in the quasi-biennial oscillation (e.g., Dunkerton, 1981a,b), the inclusion of wave transience here would have been an expensive and probably unnecessary addition to the model. Wave transience would not appear to change the low-level flow structure significantly.

Horizontal advection is represented in a crude way following Dunkerton (1979), except that the vertical dependence is now more realistic at upper levels:

$$G_{SA}(z,t) = (10\ \text{days})^{-1}\{\bar{u}(z) + 35\ \text{m s}^{-1}\} \times \exp - \left(\frac{z-50}{10}\right)^2, \quad (3.5)$$

every other 90 days, so as to semiannually relax the mean flow to -35 m s^{-1} around the stratopause. Finally, the tidal diffusion and deceleration are as in (2.1) and (2.2). The 0.3 m^2 s^{-1} component is added to ensure adequate diffusion in the region of the quasi-biennial oscillation. Also, the exponential tail of ν below 85 km should be regarded as due to other breaking waves, such as gravity waves, of which more will be said shortly.

For model parameters we take $N = 0.02$ s^{-1}, $\beta = 2.29 \times 10^{-11}$ m^{-1} s^{-1}, $a = 6.37 \times 10^6$ m, $\Delta z = 250$ m, and $\Delta t = 86\,400$ s. The zonal wavenumbers are

$$k_{KQ} = a^{-1}, \quad (3.6a)$$

$$k_{RG} = 4a^{-1}, \quad (3.6b)$$

$$k_{KS} = 2a^{-1}, \quad (3.6c)$$

with phase speeds[4]

$$c_{KQ} = 10\ \text{m s}^{-1}, \quad (3.7a)$$

$$c_{RG} = -20\ \text{m s}^{-1}, \quad (3.7b)$$

$$c_{KS} = 50\ \text{m s}^{-1}, \quad (3.7c)$$

and forced wave action fluxes

$$B_{KQ}(17) = 6 \times 10^{-3}\ \text{m}^2\ \text{s}^{-2}, \quad (3.8a)$$

$$B_{RG}(17) = -B_{KQ}(17), \quad (3.8b)$$

$$B_{KS}(17) = 2 \times 10^{-3}\ \text{m}^2\ \text{s}^{-2}. \quad (3.8c)$$

The lower boundary condition is

$$\bar{u}(17) = -5\ \text{m s}^{-1}. \quad (3.9)$$

At the beginning of the next section, this model is integrated without the small-scale waves in order to determine the relevant parameters for the latter. These waves are incorporated into the model using a combination of the steady wave formulations employed by Holton (1982) and Matsuno (1982). In general,

$$B(z) = B(z_s)\exp\left[\frac{z-z_s}{H} - \int_{z_s}^{z} D(z')dz'\right]. \quad (3.10)$$

As discussed by Matsuno (1982), the waves are dissipated by $D(z)$, which is given by (3.3a). As discussed by Holton (1982) however, the waves are not allowed to grow beyond their point of "saturation" where

[4] The value of c_{KQ} was chosen to artificially generate time-mean easterlies at low levels; however, it is more likely that this time-mean flow is attributable to other effects (Dunkerton, 1982c).

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

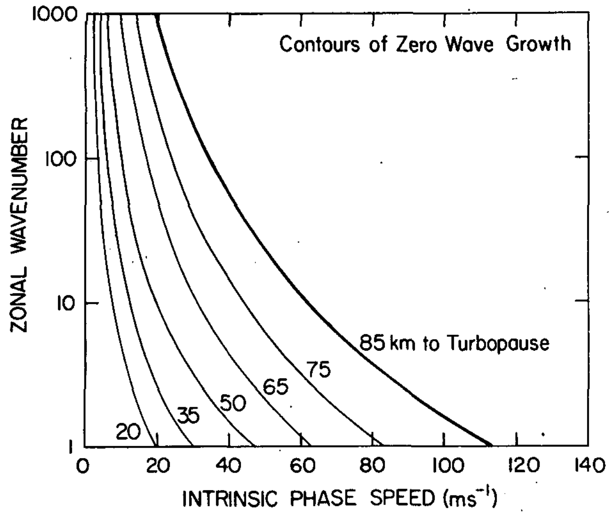

FIG. 5. Contours of zero wave growth for Kelvin and gravity waves for the dissipation rate profiles used in this study.

(3.10) implies an unstable lapse rate within the wave. If saturation occurs, we set

$$B \longrightarrow B_{\text{sat}} \equiv \frac{1}{2}\frac{k(c-\bar{u})^3}{N}, \tag{3.11}$$

(Lindzen, 1981; Dunkerton, 1982a; Holton, 1982). In (3.10), z_s is the nearest point of saturation beneath the level in question (or 17 km). It is possible, of course, for a wave to become saturated and then "unsaturated" during the course of its vertical propagation through a varying mean flow.

This procedure differs from the transient, conservative wave approach used by Dunkerton (1982b). It was considered necessary to explicitly include dissipation in the present model, because the gravity waves always seem to come fairly close to their critical levels at all times *when the time-mean state of the atmosphere is included in the model*, unlike the situation in Fig. 4. As the Doppler-shifted phase speed vanishes, the dissipation markedly increases, implying that an *a priori* assumption of conservative waves, as in Dunkerton (1982b), would not be appropriate here. This, in fact, is the primary complication that arises when the time-mean state is included.

4. Results and discussion

a. "Basic state" simulation

As discussed by Dunkerton (1979), the behavior of steady, dissipated waves is governed by the relative magnitudes of the density scale height H and the *effective dissipation scale height*

$$H_D \equiv \{\sum_i H_i^{-1}\}^{-1}. \tag{4.1}$$

In our case we have

$$H_\alpha = k\hat{c}^2/N\alpha, \tag{4.2a}$$

$$H_\nu = k\hat{c}^4/2\nu N^3, \tag{4.2b}$$

for the gravity and Kelvin waves, where $\hat{c} = c - \bar{u}$. Where H_D is greater (less) than H, the waves grow (decay) with height. Continued wave growth implies the likelihood of saturation. Fig. 5 displays the contours of zero wave growth as a function of k and $\hat{c}$, assuming the damping rate profiles used in this study. At a given level, waves to the right (left) of the curve are growing (decaying), assuming they are not saturated. In general, the smaller zonal wavelength implies better vertical propagation due to the larger vertical group velocity. (Extremely small scales will be evanescent, however.) Following earlier authors, we might identify the range of zonal wavenumbers

$$100 < ka < 1000, \tag{4.3}$$

with the most relevant small-scale waves in the atmosphere. The apparent ease with which these waves propagate into the lower thermosphere in the model suggests their prevalence in the equatorial lower thermosphere, perhaps much like the situation in midlatitudes.

Fig. 5 indicates that a wavenumber 2, 50 m s^{-1} Kelvin wave will propagate into the lower mesosphere before decaying. The numerical model without small-scale waves verified this, as shown in Fig. 6. In this simulation, we observe time-mean westerlies over most of the model mesosphere. The descent of the

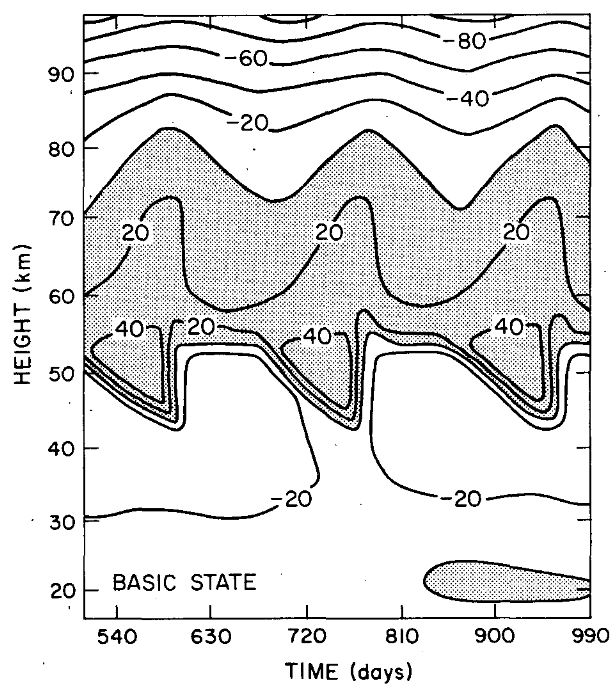

FIG. 6. Basic state model simulation without small-scale gravity waves.

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

semiannual westerlies into the stratosphere has a slight quasi-biennial modulation (Wallace, 1973; Dunkerton, 1979). Westerly phase descent is most vigorous when westerlies are absent from the quasi-biennial oscillation, and *vice versa*. The simulated quasi-biennial oscillation has a period of slightly less than two years.

Horizontal advection and the diurnal tide have generated easterlies in their respective regions. In the stratosphere, the time-mean easterlies are comparable to or slightly greater than those found by Belmont *et al.* Above the mesopause, the easterlies continue to grow with height, probably due to the absence of any other thermospheric processes in the model, such as ion drag (Matsuno, 1982).

Above 30 km, there is a simple semiannual oscillation having an amplitude maximum slightly below 50 km. Above 60 km, the Kelvin wave influence is diffusive in character, leading to an incorrect phase relationship between the stratopause and mesopause oscillations. The latter is of order 20 m s^{-1}.

This simulation indicated that the Kelvin wave can make some contribution to the upper mesospheric momentum budget. In fact, this contribution might be expected to *increase* when the upper mesospheric flow is made more easterly, as will be seen in the following discussion.

b. Gravity wave pairs

Because there does not appear to be any preferred sign for gravity wave phase speeds in the tropics, we have chosen to incorporate these small-scale waves in pairs having equal and opposite phase speed. Furthermore, we shall employ equal and opposite momentum fluxes for each pair by the same reasoning. Physically, these assumptions seem reasonable, particularly if tropical convection is a source of these waves.

To assess the relevant gravity wave phase speeds for this model, Fig. 7 has been constructed from the output of Fig. 6. It is expected, as a first approximation, that the most relevant gravity waves for stress in the upper atmosphere are those pairs for which one component of the pair is absorbed somewhere in the lower atmosphere (below 70 km), while the other component is freely propagating. Waves inside the shaded region are forbidden as they encounter critical levels at some height. Waves immediately outside the forbidden region will also, in general, be severely attenuated by dissipation. Fig. 7 indicates that *for this model*, an easterly gravity wave of approximately −40 m s^{-1} will be of primary importance in the upper model mesosphere. (The reader is reminded that these kinds of diagrams are very sensitive to the low-level mean flow structure, so different conclusions will be obtained in different cases.)

Furthermore, this −40 m s^{-1} wave will be semiannually absorbed at lower levels. Momentum deposition associated with such a wave is expected to be greatest when the strongest westerlies are established in the stratopause oscillation.

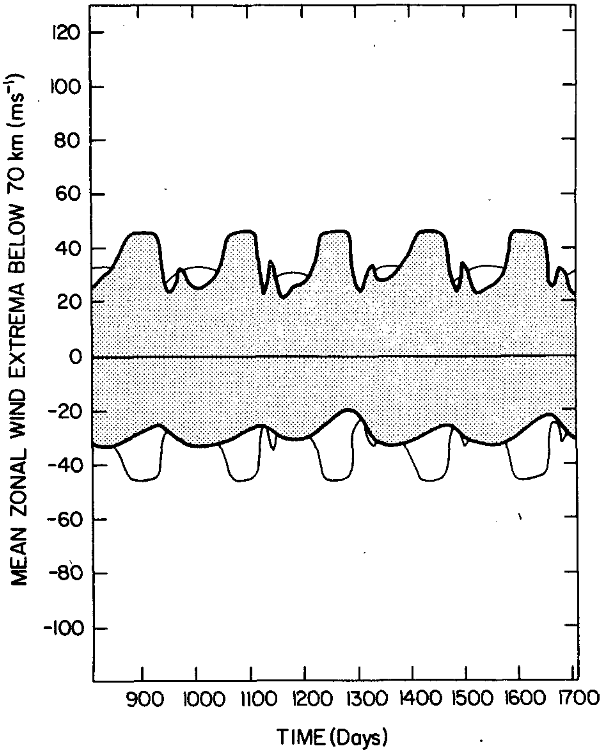

FIG. 7. Mean zonal wind extrema below 70 km for the model simulation of Fig. 6. Waves inside the thin lines but outside the forbidden (shaded) region are "most relevant" in the sense that the opposite phase speed wave is absorbed, assuming approximate symmetry about $c = 0$.

A number of simulations were done in which this wave, and its mirror image +40 m s^{-1} wave, were included. A second, higher phase speed pair was also included in these experiments. The forced momentum fluxes were varied over a "reasonable" range; i.e., comparable to values used by Holton (1982) and Matsuno (1982). While there is no way, at present, to assign precise values to these and the other wave parameters, the following experiments might yield some comparative information for later observational studies.

c. The self-enhancing mesopause semiannual oscillation

Mesopause semiannual oscillations generated by this model (with gravity waves) are *self-enhancing* in the sense that if wave parameters are adjusted so as to cause one phase of the oscillation to be stronger, the opposite phase will also be strengthened. It was found, for example, that a single easterly gravity (EG)

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

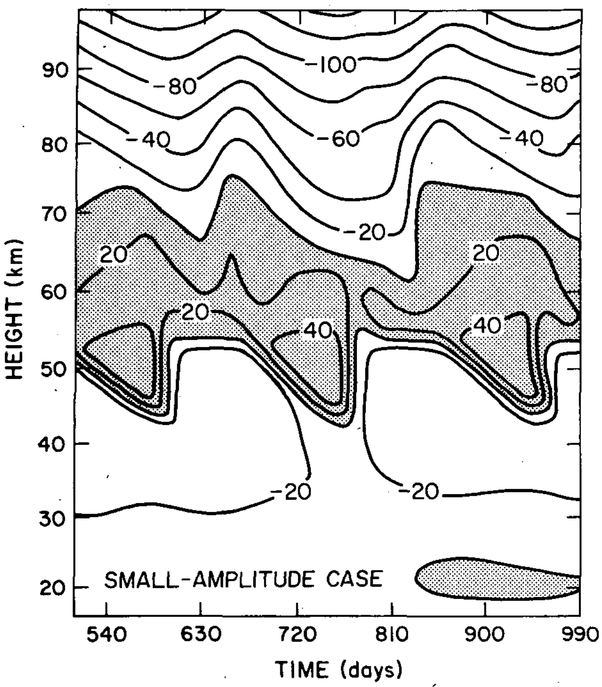

FIG. 8. As in Fig. 6, but with small-scale gravity waves.

wave −40 m s^{-1} with adequate amplitude would cause a dramatic increase in the strength of the mesopause semiannual oscillation. In this case, the opposite westerly gravity (WG) wave +40 m s^{-1} was not required; here, the Kelvin wave acceleration was increased in the stronger easterly winds induced by the easterly gravity wave in the upper mesosphere.

Essentially, this situation prevailed in a slightly more complicated experiment shown in Fig. 8. Gravity wave parameters were taken to be

$$k_{WG} = k_{EG} = 200 \text{ a}^{-1}, \tag{4.4a}$$

$$c_{WG}^{(1)} = -c_{EG}^{(1)} = 40 \text{ m s}^{-1}, \tag{4.4b}$$

$$c_{WG}^{(2)} = -c_{EG}^{(2)} = 60 \text{ m s}^{-1}, \tag{4.4c}$$

$$B_{WG}^{(1)}(17) = -B_{EG}^{(1)}(17) = 1.5 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}, \tag{4.4d}$$

$$B_{WG}^{(2)}(17) = -B_{EG}^{(2)}(17) = 10^{-5} \text{ m}^2 \text{ s}^{-2}. \tag{4.4e}$$

The zonal wavenumber is typical of that found in observations (Matsuno, 1982), but model results are insensitive to this choice. These momentum fluxes are not overly large; the larger of the two pairs, for example, has a momentum flux 1/40th that of the equatorial waves used here.

Dynamically, the relevant interaction in Fig. 8 is between the Hirota Kelvin wave and the $EG^{(1)}$ wave. The $WG^{(1)}$ wave also contributes to the westerly accelerations at the mesopause, but no actual westerlies, in an absolute sense, are observed above the mesopause. The easterly gravity wave has prepared the way for the Kelvin and westerly gravity waves by inducing an easterly flow which thereby enhances the vertical propagation of these waves (see Fig. 5). This causes the mesopause oscillation to be more than twice as strong as was observed in Fig. 6, and the phase relationship between the stratopause and mesopause oscillations is greatly improved. The easterly wave has also brought time-mean easterlies into the upper mesosphere, agreeing with Fig. 2. The high phase speed pair makes only a few percent contribution to this model simulation.

There is a visible modulation of the mesopause semiannual oscillation by the quasi-biennial oscillation. This causes upper mesospheric easterlies to be strongest when easterlies are weakest in the stratospheric flow, which occurs when the Kelvin wave (KQ) commences the westerly phase of the quasi-biennial oscillation. Observations, which have very limited data records, are unclear as to whether or not such a modulation exists in the mesosphere. There is no doubt, however, that a quasi-biennial modulation is observed in the stratopause oscillation (Wallace, 1973; Dunkerton, 1979).

When the time-mean is removed from Fig. 8, the dynamical separation between the stratopause and mesopause oscillations is more evident (Fig. 9). In the transition region (55–65 km), upward diffusion of Kelvin-wave-induced westerly momentum is present, creating an irregular appearance in the mean zonal wind field there.

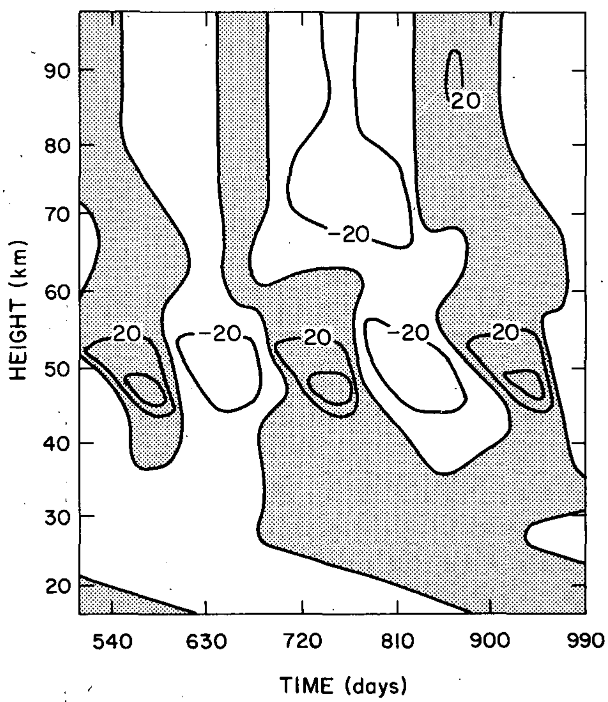

FIG. 9. As in Fig. 8, but with time-mean removed at each level.

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

d. Sensitivity of the upper-level flow

Even this simplified numerical model permits many different combinations of wave parameters and functional dependences. Of the few dozen or so experiments that were within our budget, model behavior in the vicinity of the mesopause could be broadly categorized in three ways. First, a rather weak *diffusion-induced* mesopause semiannual oscillation was observed in experiments without small-scale gravity waves, or with inadequate gravity wave amplitudes (Fig. 6). Second, a moderate-amplitude mesopause oscillation, distinct from the stratopause oscillation and having a correct phase relationship with the latter has been observed, as shown in Figs. 8 and 9. A third class of experiments yielded a much larger mesopause oscillation, sometimes with a less realistic phase dependence in height. These simulations involved extremely large gravity wave accelerations at upper levels. Fig. 10 shows an example of this third, "unrealistic" class of model results in which gravity wave parameters were identical to those above except that

$$B_{\mathrm{WG}}^{(1)}(17) = -B_{\mathrm{EG}}^{(1)}(17) = 2 \times 10^{-4}\ \mathrm{m^2\ s^{-2}}, \quad (4.5a)$$

$$B_{\mathrm{WG}}^{(2)}(17) = -B_{\mathrm{EG}}^{(2)}(17) = 4 \times 10^{-5}\ \mathrm{m^2\ s^{-2}}, \quad (4.5b)$$

and the semiannual advection relaxed the mean flow to $-25\ \mathrm{m\ s^{-1}}$ (instead of $-35\ \mathrm{m\ s^{-1}}$ previously). These changes greatly increased the easterly wave accelerations in the upper mesosphere, leading to dramatically increased westerly wave accelerations in the presence of the increased wave forcings. Larger relative westerlies further enhanced the easterly accelerations, resulting in an almost explosive growth of the oscillation compared to that shown in Fig. 8. Note that absolute westerlies are observed in Fig. 10 at and above the mesopause, albeit for a very brief period of time.

In view of the highly "asinusoidal" appearance of this mesopause oscillation, it seems doubtful that such large gravity wave accelerations will be prevalent in the equatorial mesosphere (at least without being balanced by other forces). However, this class of model results reminds us of the sensitivity of this region to low-level forcings, and might actually explain some of the variability in the observed mesopause semiannual oscillation (e.g., the appearance of absolute westerlies at 80 km, and the vigor of the easterly phase descent). Part of this variability could, of course, be attributed to the annual cycle.

e. Additional Kelvin wave

The extreme high phase speed Kelvin wave found by Salby *et al.* (1982) would be expected to contribute to the momentum budget of the mesopause semiannual oscillation in the westerly acceleration phase. It was found that including a third Kelvin wave in the model of zonal wavenumber 2, phase speed 100 m $\mathrm{s^{-1}}$, and forced momentum flux $\sim$10% of $B_{\mathrm{KS}}(17)$ had the effect of increasing the mesopause semiannual oscillation amplitude by as much as 20 m $\mathrm{s^{-1}}$. Larger momentum fluxes for this wave, however, resulted in an unrealistic westerly time-mean flow at the mesopause.

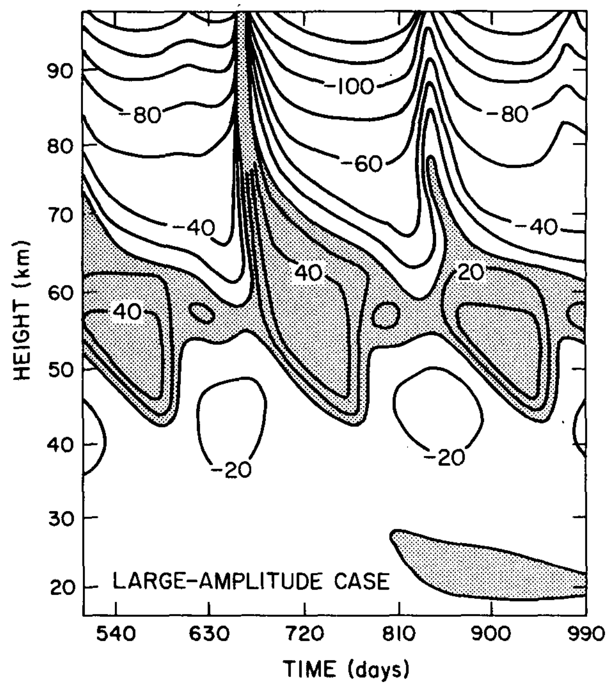

FIG. 10. As in Fig. 8, but with larger gravity wave forcings.

It will be of interest to see whether LIMS data in the April–May period reveals any *easterly* equatorial waves in the mesophere. The absence of significant easterly power in the February period is consistent with theory (M. Salby, personal communication, 1982). Determination of the easterly momentum source in the mesopause semiannual oscillation remains perhaps the most pertinent observational question at this time. Particular emphasis will need to be placed on the role of horizontal momentum fluxes associated with quasi-stationary Rossby waves at the equatorial zero-wind line (Dunkerton, 1982c).

5. Conclusion

An explanation of the mesopause semiannual oscillation suggests that the selective transmission of vertically-propagating gravity and Kelvin waves is responsible for momentum deposition leading to this oscillation. No *in situ* semiannual forcing is required at the mesopause, according to this model.

Very little is currently known observationally about these waves in the equatorial upper meso-

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC

sphere. Model results can be very sensitive to the wave parameters employed; however, the primary intent of this paper has been to demonstrate the plausibility of this mechanism, rather than confirming exact values for the wave parameters.

Model output as shown in Fig. 8 bears little overall resemblance to the many published observational profiles from which the time-mean has been removed. The time-mean flow is crucial to wave propagation since the wave, mean-flow interactions are inherently nonlinear, being dependent on the *absolute* mean wind, and the linear superposition of mean flows is not valid.

Acknowledgments. The author thanks K. Hamilton and I. Hirota for helpful discussions and for allowing their observational results to be reproduced here. Helpful comments from R. A. Plumb and an anonymous reviewer are also acknowledged.

REFERENCES

Belmont, A. D., D. G. Dartt and G. D. Nastrom, 1974: Periodic variations in stratospheric zonal wind from 20–65 km, at 80N to 70S. *Quart. J. Roy. Meteor. Soc.*, **100**, 91–99.

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

——, 1981a: Wave transience in a compressible atmosphere, Part I: Transient internal wave, mean-flow interaction. *J. Atmos. Sci.*, **38**, 281–297.

——, 1981b: Wave transience in a compressible atmosphere, Part II: Transient equatorial waves in the quasi-biennial oscillation. *J. Atmos. Sci.*, **38**, 298–307.

——, 1982a: Wave transience in a compressible atmosphere, Part III: The saturation of internal gravity waves in the mesosphere. *J. Atmos. Sci.*, **39**, 1042–1051.

——, 1982b: Stochastic parameterization of gravity wave stresses. *J. Atmos. Sci.*, **39**, 1711–1725.

——, 1982c: Laterally-propagating stationary Rossby waves in the easterly acceleration phase of the quasi-biennial oscillation. Submitted to *Atmos.-Ocean.*

Fels, S. B., 1982: A parameterization of scale-dependent radiative damping rates in the middle atmosphere. *J. Atmos. Sci.*, **39**, 1141–1152.

Hamilton, K. P., 1981: The vertical structure of the quasi-biennial oscillation: Observations and theory. *Atmos.-Ocean*, **19**, 236–250.

——, 1982: Rocketsonde observations of the mesospheric semiannual oscillation at Kwajalein. *Atmos.-Ocean* (in press).

Hirota, I., 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.

——, 1980: Observational evidence of the semiannual oscillation in the tropical middle atmosphere—a review. *Pure Appl. Geophys.*, **118**, 217–238.

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

——, 1982: The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere. *J. Atmos. Sci.*, **39**, 791–799.

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

——, and W. M. Wehrbein, 1980: A numerical model of the zonal mean circulation of the middle atmosphere. *Pure Appl. Geophys.*, **118**, 284–306.

Lindzen, R. S., 1981: Turbulence and stress due to gravity wave and tidal breakdown. *J. Geophys. Res.*, **86C**, 9707–9714.

Matsuno, T., 1982: A quasi one-dimensional model of the middle atmosphere circulation interacting with internal gravity waves. *J. Meteor. Soc. Japan*, **60**, 215–226.

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.

——, and A. D. McEwan, 1978: The instability of a forced standing wave in a viscous stratified fluid: A laboratory analogue of the quasi-biennial oscillation. *J. Atmos. Sci.*, **35**, 1827–1839.

Salby, M., D. Hartmann, P. Bailey and J. Gille, 1982: Evidence for equatorial Kelvin modes in Nimbus 7 LIMS. Presented at Estes Park MST Radar Workshop.

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

Wehrbein, W. M., and C. B. Leovy, 1982: An accurate radiative heating and cooling algorithm for use in a dynamical model of the middle atmosphere. *J. Atmos. Sci.*, **39**, 1532–1544.

Unauthenticated | Downloaded 05/08/21 06:44 AM UTC