Phase Alignment of the Tropical Stratospheric QBO in the Annual Cycle

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ABSTRACT

This paper investigates the occurrence of phase alignment of the tropical stratospheric quasi-biennial oscillation (QBO) with the annual cycle. First, updating previous studies, observational results are shown for NCEP re-analysis data and Singapore radiosondes: both datasets show strong phase alignment of the QBO at 24.5 km. Phase alignment is investigated in a 3D mechanistic stratospheric model including explicit large-scale planetary waves, forced by a lower boundary geopotential anomaly, and a simple equatorial wave parameterization. The model simulates a QBO-like oscillation, with the period depending on the lower boundary momentum flux of the parameterized waves. Phase alignment is manifested in two different ways. First, simulated oscillations of both integer and noninteger year periods are shown to lock on to a certain phase of the annual cycle. Second, when the magnitude of the lower boundary momentum flux is varied about a range implying oscillation period close to 2 yr, the period of the resulting oscillation is exactly 2 yr for a finite range of such magnitude. Analysis of the 3D model results suggest that the phase alignment is due largely to the annual cycle in tropical upwelling. This hypothesis is supported by simulations with a 1D equatorial model including both parameterized waves and seasonally varying upwelling. The oscillations in this model show significant phase alignment when the upwelling parameters are tuned to correspond to the 3D model, although the phase alignment is weaker than that seen in the 3D model.

1. Introduction

The quasi-biennial oscillation (QBO) is a striking and well-known feature of the tropical stratospheric circulation. Many aspects of the QBO have been recently reviewed in the paper by Baldwin et al. (2001). Here we focus on one aspect of the QBO, which is the observed irregularity of the oscillation and a possible interpretation as an interaction with the annual cycle. The period of the QBO is observed to vary between 22 and 34 months. One possible explanation for irregularity is clearly that the wave forcing that is needed to drive the QBO is itself irregular. However, another possibility is interaction between the QBO and the annual cycle. The fact that the average period of the QBO (28 months) is not an integer multiple of the annual cycle inevitably implies that any interaction with the annual cycle will imply irregularity. One indication of interaction with the annual cycle is the seasonal preference for a particular stage in the evolution of the QBO. Dunkerton and Delisi (1985) and Dunkerton (1990) considered observational data of the onset times of the westward phase of the QBO at the 50-mb (21 km) height level and noted significant seasonal preference with, in particular, very few such onsets between August and December. Such a variation of the QBO with respect to the annual cycle will here be referred to as phase alignment in the annual cycle (abbreviated from here on as “phase alignment”). Seasonal modulation of the QBO has also been revealed by empirical orthogonal function (EOF) analysis (1993) and by nonlinear principal component analysis (2002), though both these papers show the clearest seasonal modulation in “phase progression” with seasonal dependence of the rate of change of phase, rather than phase alignment, with seasonal dependence of the likelihood of a given phase. We discuss this point further in the concluding section of the paper. Kinnersley and Pawson (1996) carried out a limited numerical study of phase alignment, which showed an increased descent rate of the westward zero wind line between May and June. They suggested that this was due in part to weaker vertical ascent at that time of year. However, their numerical simulations lasted only for two QBO cycles, making it difficult to draw firm conclusions.

The aim of this paper is to examine in more detail at the occurrence and possible cause of QBO phase align-
2. Phase alignment and irregularity of the QBO in observational data

We have analyzed monthly averaged data from Singapore (1.3°N, 103.1°E) radiosondes from 1953 to 2002, and NCEP reanalysis data for the years 1960–99. NCEP data for years 1948–58 do not seem to include a clear QBO and have therefore been discarded. We focus in particular on the 24.5-km (in log pressure height, corresponding to 30 mb) level. This is higher than used in the studies by Dunkerton and Delisi (1985) and Dunkerton (1990), but at lower levels not only is the QBO signal weaker, but there is the potential complication of direct influence of annual cycle signals from the tropical troposphere.

Figure 1 shows a histogram giving the number of times that the $\pi = 0$ windline at 24.5 km, according to both the radiosonde data and the NCEP reanalysis data, falls into each month and distinguishing between the transition from eastward to westward (denoted by $\pi = 0_{\text{ew}}$; Fig. 1a) and the transition from westward to eastward (denoted by $\pi = 0_{\text{we}}$; Fig. 1b). Specifically, the $\pi = 0$ windline is counted in a certain month if the monthly mean wind changes sign in that month from the preceding month. Figure 2 shows the distribution of periods (as measured by time between successive westward-to-eastward wind transitions $\pi = 0_{\text{we}}$ in the radiosonde data). The distribution of periods for the NCEP data (not shown) is similar to that for the radiosonde data.

The plots shown here are constructed from data that includes the seasonal cycle, in contrast to the deseasonalized data used by Dunkerton and Delisi (1985) and Dunkerton (1990). This is because possible mechanisms for causing phase alignment may be more easily identified and understood by using the raw data rather than processed data.

Several broad features of the radiosonde data and the NCEP reanalysis data are in good qualitative agreement. There is evidence of phase alignment for both transitions $\pi = 0_{\text{ew}}$ and $\pi = 0_{\text{we}}$. In particular, for the $\pi = 0_{\text{ew}}$ transition, the majority fall between April and June, with very few in the range from August to December, as was found by Dunkerton (1990). For the $\pi = 0_{\text{we}}$, the pattern is less clear, but both datasets show few transitions from May to July. For the period 1960–99, both datasets show some cycles with periods of 18–24 months and most cycles with periods distributed over the range 24–36 months, with periods greater than 30 months being relatively infrequent.

Figure 1 corresponds to Fig. 18 in Dunkerton and Delisi (1985). The results are not directly comparable because of the different height levels used and the use
of the zonal mean wind here, but nonetheless they are qualitatively similar.

### 3. The 3D mechanistic model

The model used in this work was written by Dr. R. Saravanan and is the same as that used in Scott and Haynes (1998) and subsequent papers. It solves the primitive equations using a spherical harmonic representation in the horizontal and a grid representation in the vertical. The spherical harmonic series are truncated anisotropically, including harmonics with total wavenumber up to and including 21, but only mean and wave-1 components in longitude. The severe longitudinal truncation used here is incorporated to allow many multiyear simulations to be carried out, which is necessary to allow careful investigation of parameter space of possible model runs once a tropical QBO has been incorporated into the model. This truncation is justified, to a degree, by the observation that it is the lowest zonal wavenumbers that dominate the large-scale evolution of the stratosphere which is under investigation here. This approach has been used by Scott and Haynes (1998, 2000, 2002) to address other issues in the seasonal and interannual variation of the stratosphere with apparently encouraging results. See those papers for further discussion and justification.

The model uses pressure as the vertical coordinate, with levels chosen to be equally spaced in log pressure height. The model has height range from 10 to 70 km. The top 10 km of the model are dominated by the use of a “sponge layer” to prevent spurious wave reflection.

Damping terms are included in the form of Newtonian cooling, Rayleigh friction, and small-scale damping in the form of \( V^2 \) hyperdiffusion. Of these, the most relevant to the investigations here is the Newtonian cooling, through which the seasonal cycle is represented by a model relaxation to a given time-dependent potential temperature distribution. This radiative equilibrium potential temperature is calculated as a sinusoidally varying superposition of two potential temperature distributions, representing summer and winter. These in turn are calculated so as to be in thermal wind balance with prescribed idealized zonal mean wind profiles for summer and winter. For details of these wind profiles and temperature distributions, see the appendix of Scott and Haynes (1998).

Model variables are output every 10 days, so that the output time divides 30 days (which is used as the monthly division time), and 360 days exactly (which is used as the length of year). This avoids confusing stroboscopic effects in the analysis of the long-period variability.

Waves can be forced in the model by imposing a zonal wavenumber-1 perturbation in the lower boundary geopotential height, \( \Phi_{LB} \), as

\[
\Phi_{LB} = \begin{cases} 
\frac{1}{2} \Phi_0 \cos(\lambda) \left[ 1 + \cos(6(\phi - 60^\circ)) \right], & \phi > 30^\circ \text{N} \\
0, & \text{otherwise}, 
\end{cases}
\]

where \( \lambda \) is longitude, \( \phi \) is latitude, and \( \Phi_0 \) is the amplitude of the perturbation. Hence, the wave forcing is only imposed in the Northern Hemisphere (NH), with the forcing amplitude nonzero between 30°N and the Pole, with maximum at 60°N. After an initial spinup period \( \Phi_{LB} \) is kept constant in time. We note here that the imposed annual cycle in the global mean zonal wind, as described above, is necessary to produce a time dependence in the wave Eliassen–Palm (EP) fluxes (given that the lower boundary wave forcing remains constant). Scott (2002) describes the time varying meridional circulation that results in this situation.

The motivation of this paper is to investigate the possibility of phase alignment occurring as a result of the internal QBO dynamics, not as a result of externally imposed irregularity. Following Plumb (1977), we choose the simplest possible wave parameterization scheme that leads to a QBO, with two symmetric gravity waves localized to the Tropics. The vertical momentum flux (at the equator) due to the \( j \)th wave is taken to be of the form

\[
F_j(z) = F_j(z_i) \exp \left\{ - \frac{N\mu}{k_j (\mu^2 z^2 - c_j^2)} dz \right\},
\]

where \( u(z, t) \) is the zonal mean equatorial wind, \( N \) is the buoyancy frequency (\( 2 \times 10^{-5} \text{ s}^{-1} \)), \( \mu \) is the wave damping rate (\( 10^{-6} \text{ s}^{-1} \)), \( k_j \) is the longitudinal wavenumber of the \( j \)th wave (\( 6 \times 10^{-6} \text{ m}^{-1} \)), \( c_j \) is the phase speed of the \( j \)th wave (\( 20 \text{ m s}^{-1} \) for \( j = 1 \); \( -20 \text{ m s}^{-1} \) for \( j = 2 \)), and \( z_i \) is the height at which the waves are regarded as forced (taken to be 10 km for the simulations reported here). Parameter values are chosen to be broadly consistent with those of Plumb (1977).

Again following Plumb (1977), the momentum flux at the lower boundary \( z_i \) is given by

\[
F_j(z_i) = \begin{cases} 
F_0: & u(z_i, t) < c_1 \\
0: & u(z_i, t) \geq c_1,
\end{cases}
\]

\[
F_j(z_i) = \begin{cases} 
-F_0: & u(z_i, t) > c_2 \\
0: & u(z_i, t) \leq c_2.
\end{cases}
\]

The value of \( F_0 \) (units: \( \text{m}^2 \text{s}^{-1} \)) determines the period of the resulting QBO. Broadly speaking, the period of the QBO reduces as \( F_0 \) increases. The zonal wave force \( f(\phi, z) \) due to the dissipation of the waves is then given by
The oscillation for fixed $F_0$ is given by

$$f(\phi, z) = -\frac{1}{\rho}k(\phi) \sum_{j=1}^{\infty} \frac{\partial F_j}{\partial z},$$

(3)

where the function $k(\phi)$ describing the latitudinal variation of the force is given by

$$k(\phi) = \begin{cases} \cos \frac{\pi}{2} \left( \frac{\phi}{\phi_{QBO}} \right), & |\phi| = \phi_{QBO} \\ 0, & \text{otherwise,} \end{cases}$$

and the latitudinal width of the QBO, $\phi_{QBO}$, is taken to be 20°. We note here that, following Haynes (1998), it is not necessarily true that the latitudinal structure of the QBO wave forcing needs to follow the latitudinal structure of the QBO itself. However, further exploration of this point lies beyond the scope of this work, and the given latitudinal dependence in forcing is satisfactory for current purposes.

To limit the height extent, the wave-induced force is taken to vanish above 31.3 km. A further difference from the model considered by Plumb (1977) is the inclusion of a switching condition at the lower boundary. Plumb (1977) noted that vertical viscosity was essential for the parameterization scheme to give rise to an oscillating wind pattern, however, adding vertical viscosity to the 3D model has various detrimental factors. For example, it inhibits the internal mode of oscillation found by Scott and Haynes (1998). The switching condition is used at the lower boundary condition to prevent the build up of shear layers at the bottom of the model. This works by switching off the forcing of the gravity wave $j$ when the zonal mean wind speed at $z_j$ exceeds the phase speed $c_j$ until the zonal wind at $z_j$ has changed sign. A saturation condition [similar to that used by Kinnersley and Pawson (1996)] is used to prevent the discretization scheme giving rise to winds far exceeding the wave phase speed.

With these ingredients, large-scale waves explicitly simulated and forced by imposed lower boundary forcing in the extratropics plus parameterized tropical wave forcing, the model is able to simulate a QBO and may be used as a tool to investigate the interactions between the QBO and the large-scale circulation. A large set of experiments with different values of $F_0$ and $\Phi_0$ showed behavior as expected from previous studies of the QBO. In particular, it was found that oscillations occurred if $F_0$ exceeded a critical value for given $\Phi_0$, and that increases of $F_0$ above the critical value reduced the period of the oscillation. It was also found that as $\Phi_0$ increased, the critical value of $F_0$ also increased and the period of the oscillation for fixed $F_0$ also increased. This latter behavior almost certainly arises from the fact that upwelling velocity in the Tropics increases as $\Phi_0$ increases, and this has the effect of slowing, or even halting, the downward phase propagation associated with the QBO (see, e.g., Dunkerton 1991, 1997). This behavior is summarized in Fig. 3.

There are two problems associated with the parameterization scheme. The first is that there is a limit to the length of period of QBO that can be obtained in the model: for small values of the forcing parameter $F_0$ (i.e., tending toward a longer period), the parameterization scheme no longer gives rise to an oscillation (see Fig. 3). This is as expected by analogy with the results of Plumb (1977). Second, for strong geopotential wave forcing and certain values of $F_0$, the parameterization scheme gives rise to particularly irregular oscillations in which certain eastward QBO descents are “stalled”; that is, at the bottom level of the QBO, the eastward phase persists for much longer than normal. These stallings are reminiscent of what is sometimes seen in observations (e.g., in 2001), but sometimes last significantly longer. It appears that the modeled stallings arise from some aspect of the numerical scheme. To avoid the issue of stallings complicating the question of phase alignment, we avoid using QBO parameters that give rise to the stalling phenomenon.

4. Evidence of phase alignment in the 3D model

a. Phase readjustment of integer year period QBO

If there was no tendency for phase alignment of the QBO in the annual cycle, then the evolution of the QBO during some time period would be independent of the phase of the QBO in the annual cycle at the beginning of that period. To see if this is true, we examine the evolution of a QBO with integer year period, for four different experiments with the initial QBO phase in the annual cycle differing by phase $\pi/2$ between each.

To initialize the QBO in a certain phase with the annual cycle, care has to be taken, because the QBO parameterization scheme described in Eqs. (2) and (3) does not specify any initial conditions: the QBO will evolve from any perturbation of nonzero equatorial winds [this is described in Plumb (1977)]. To initialize the phase of the QBO with the annual cycle, the equatorial winds have to be initialized appropriately. This is done by initializing each model run with a relaxation scheme applied in the Tropics to relax the zonal mean wind toward the desired QBO winds.
The wave forcing parameter $F_0$ is chosen to give a QBO of average period 2 yr; for $F_0 = 285$ m, trial and error leads to taking $F_0 = 1.2$.

Figure 4 shows the evolution of the QBO in the annual cycle for four such experiments. For each model run, the time evolution of the QBO phase $\pi = 0_{kw}$ at 22.7 km (in log pressure height, corresponding to 39 mb) is plotted. It can be seen that although the QBO is initially in a different phase of the annual cycle for the four different runs, after an “adjustment time” has elapsed (up to 5 yr), the chosen QBO phase always falls within the same region of the annual cycle (about 0.2–0.5: around NH autumn) for all four experiments. In other words, the QBO aligns itself into a naturally preferred phase with the annual cycle.

To investigate how much of the phase alignment seen in Fig. 4 is due to the extratropical geopotential wave forcing, we carry out the same set of experiments but with $\Phi_0 = 0$. In this case, $F_0 = 0.93$ gives a 2-yr QBO. Corresponding results are shown in Fig. 5. Some evidence of phase preference is seen, but it is no longer consistent throughout the four runs: three of the runs approach the same phase, the fourth approaches a phase about half a year out with the others. The final phase that each QBO settles into is much more settled than for the $\Phi_0 = 285$ m case, but the transition time to the preferred phase is considerably longer (up to about 12 yr).

b. Preference for integer year period QBO

In the absence of QBO phase alignment, one would expect the period of the QBO to vary smoothly with the parameterized QBO forcing value $F_0$. The phase alignment demonstrated in section 4a leads to the question of whether the QBO has a natural preference for periods of an integer number of years. To see if this is the case, we carry out experiments varying $F_0$ around the values that give 2- and 3-yr period oscillations. Figure 6 shows the variation of the period of oscillation with $F_0$ for experiments with $\Phi_0 = 285$ m.

Figure 6a shows that there is a strong preference for a 2-yr QBO. There is a range of $F_0$ values that give an oscillation period of 2 yr. However, Fig. 6b shows that there does not appear to be any preference for a 3-yr QBO, nor indeed for a 2.5-yr QBO. One reason for the lack of preference for a 2.5- and 3-yr QBO at $\Phi_0 = 285$ m may be the fact that for the weaker wave forcing values $F_0$ required to give these periods, stallings are much more common, and the resulting irregularity makes the QBO period much less easy to estimate. Whether there would be 2.5- or 3-yr period preference
in the absence of the stalling phenomenon is not known. What is clear is the strong preference for the 2-yr QBO.

Again for comparison, we look at the corresponding results for $F_0 = 0$. Figure 7a shows results for runs giving a QBO of period around 2 yr, Fig. 7b for around 2.5 yr, and Fig. 7c for around 3 yr. For all three figures the change of period with $F_0$ value is much smoother than for the $F_0 = 285$ m case. However, there is still a small anomaly around 2 yr suggesting a slight preference for a QBO of exactly 2 yr (albeit for a much smaller range of $F_0$ values than gave a 2-yr QBO in the $F_0 = 285$ m case). There are also anomalies around 2.5 and 3 yr in Figs. 7b,c, respectively.

As a further comparison, we considered the “control” case with $F_0 = 0$ and no seasonal cycle. As expected, there was no integer year preference at all.

c. Phase alignment for noninteger year period QBO

To compare phase alignment in the model more directly with observations, we choose parameters that give a QBO of period similar to that observed, and in particular not close to an integer number of years (or close to an obvious fraction of integer years). Taking $F_0 = 1.07$ and $F_0 = 285$ m gives a period of 2.40 yr. To identify phase alignment, we follow the method applied in section 2 to the observations and plot the number of times a chosen QBO phase occurs at a fixed height in each month. The results are shown in Fig. 8 at a height of 25.6 km (corresponding to 26 mb). This is the model level nearest to the level of 24.5 km used for the observational analysis. We note here that this is the height at which phase alignment of the QBO is clearest in the model. The irregularity of the period at 25.6 km is shown in Fig. 9.

The model shows strong phase alignment, particularly for $F_0 = 0$, where all such phases occur between June and December. This is reminiscent of the phase alignment found in Dunkerton (1990) and of that found in Singapore rocketsondes and NCEP reanalysis data described in section 2. It is of note that the fraction of the annual cycle in which this phase does not occur differs between the 3D model and observations. This is almost certainly due to the approximate height positioning of the QBO in the model compared to observations. Since phase alignment at two different heights are clearly linked, any change in the vertical positioning of the QBO would effect the phase alignment. Due to the somewhat artificial nature of the QBO forcing in the model, particularly at the upper and lower limits of the QBO, it is difficult to match the modeled QBO height.
to that of the observed QBO (particularly when it is considered that the QBO signal in observations stretches as far as the upper stratosphere).

There are no $\pi = 0_{\text{eqw}}$ phase occurrences between $0.0-0.4$, covering about the same fraction of the annual cycle as that discussed in Dunkerton (1990). The variability of the length of the oscillations (Fig. 9) is also similar to that described in Dunkerton (1990). As in his case, the distribution shows a small skewness, with the anomalously long cycles indeed corresponding to stalled eastward phase descents.

We note that the same analysis for a model run with $F_0 = 0$ and similar period shows no obvious phase alignment and negligible irregularity.

5. Hypothesized cause of QBO phase alignment

The results of the previous section showed that there is strong phase alignment and irregularity in model simulations with a seasonal cycle and strong extratropical wave forcing, and significantly less phase alignment for model simulations with a seasonal cycle but no extratropical wave forcing.

There are at least four distinct mechanisms by which the combination of seasonal cycle and extratropical wave forcing could lead to phase alignment of the QBO. The first is that there is an interaction, in the Tropics, between the QBO and the seasonally varying upwelling. It has been suggested by various authors (e.g., Dunkerton 1991) that equatorial upwelling plays an important role in the descent rate of the QBO. There is a well-known annual cycle in tropical temperatures and in upwelling, as was discussed by Yulaeva et al. (1994), who proposed that such a cycle was due to asymmetry in extratropical wave-driving between the NH winter and Southern Hemisphere (SH) winter (due to hemispheric asymmetry in, e.g., topography and land surface contrast). Since it is to a large extent the extratropical wave forcing that drives the meridional circulation and corresponding equatorial upwelling, such asymmetry leads to stronger upwelling in NH winter than NH summer.

A second possible mechanism is direct interaction in the Tropics between forces due to waves propagating from the extratropics and the QBO. A third possible mechanism is a two-way interaction between the Tropics and the extratropics (QBO affects extratropical waves, extratropical waves affect QBO, etc.) along the lines of the biennial oscillation demonstrated by Scott and Haynes (1998). The third mechanism can be ruled out by experiments in the 3D model as described below.

In the 3D model, the use of extratropical geopotential wave forcing in the NH only is an idealization of this hemispheric asymmetry, and the resulting seasonal variation in upwelling was discussed in some detail by Scott (2002). For a model run with Newtonian cooling toward a seasonal cycle but no wave forcing ($F_0 = 0$), the radiative forcing alone drives a relatively weak cycle in equatorial upwelling (this is actually semiannual rather than annual at the equator, as one would expect). For a model run with $F_0 = 285$ m, the addition of strong extratropical wave forcing drives a considerably larger annual cycle in upwelling, with maximum upwelling occurring shortly after midwinter.

Here we hypothesize that the annual cycle in equatorial upwelling is the dominant cause of phase alignment in the QBO. This hypothesis can be tested in a very limited way in the 3D model by attempting to separate out and manipulate the zonal wave forcing of the zonal mean flow. Briefly, we note the following results. Calculating the climatological average of the seasonally varying zonal wave forcing of the zonal mean flow. Briefly, we note the following results. Calculating the climatological average of the seasonally varying zonal wave forcing of the zonal mean flow, and applying that seasonally varying forcing (without interannual variability) as an artificial forcing in a model with no explicit waves (i.e., with $F_0 = 0$) results in phase alignment that is very similar, in fact, slightly stronger, than the original. This apparently rules out the third mechanism. Furthermore, a model run with
no imposed seasonal variation of the mean flow, but retaining the seasonally varying forcing (i.e., the zonal wave forcing taken from a simulation with seasonal variation imposed as described in section 3), gives phase alignment that is similar to, but slightly weaker than, that in the simulation with the imposed seasonal variation. This emphasizes that it is the variations in the Tropics induced by wave forcing, rather than directly induced by the seasonally varying heating, that give rise to the phase alignment. To distinguish between the first and second mechanisms is difficult in the 3D model, and we therefore move to a 1D equatorial model.

A fourth possible mechanism that has been proposed for introducing phase alignment is a downward influence of the semiannual oscillation (SAO). The fact that the observations show more of an annual phase alignment than semiannual (particularly for \( \phi = 0 \), see Fig. 1b) suggests that this is not the dominant mechanism. Further, Plumb (1977) showed that there was no downward influence in the QBO forcing, at least in the case of gravity waves being radiatively damped. Viscous damping seems not to alter this significantly, with preliminary tests using the 1D model described below showing no significant downward propagation of an imposed SAO signal.

6. 1D model of QBO and equatorial upwelling

We use a 1D model to determine whether variation in upwelling gives rise to phase alignment of the QBO (i.e., the first mechanism described previously), and to investigate the combined effect of imposed upwelling and parameterized wave forcing. The time evolution of the zonal mean wind \( \bar{u}(z, t) \) in the 1D model is given by

\[
\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho} \mathcal{F} + \kappa \frac{\partial^2 \bar{u}}{\partial z^2} - w(z, t) \frac{\partial \bar{u}}{\partial z},
\]

where \( \mathcal{F} \) is the QBO wave forcing as described in section 3, \( \rho(z) \) is the density, \( \kappa \) is the vertical viscosity, and \( w(z, t) \) is the equatorial vertical upwelling. Vertical viscosity is included here to give a more realistic and smoother QBO, and to follow the practice in previous 1D QBO models.

The upwelling term in Eq. (4) is the zonal mean component of that part of the advection term from the 3D equations of motion that involves vertical velocity. The vertical velocity is split up as follows:

\[
w = w_c + w_a \cos \left( \frac{2\pi t}{T} \right) + w_{\text{QBO}},
\]

where \( w = Dz/Dr \) is the total vertical velocity, \( w_c \) is the constant component, \( w_a \) is the amplitude of annually varying component, \( w_{\text{QBO}} \) is the component due to QBO secondary circulation, and \( T \) is the year length (in seconds). The constant (in time) and annually varying component coefficients \( w_c \) and \( w_a \) are explicitly chosen. The

![Fig. 10. Period of QBO for \( F_a \) values giving \( \sim \) (a) 2, (b) 2.5, (c) 3 yr QBO for model runs with constant plus annually varying upwelling.](http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1984)061<2627:Volntdp>2.0.CO;2?journalCode=jas)
same phase alignment behavior seen in the 3D model. The parameters of the wave parameterization scheme in the 1D model are chosen so that the behavior matches that resulting from the wave parameterization scheme in the 3D model. It does not suffice to use precisely the same parameters in both because of intrinsic differences between the 3D model and the 1D model (e.g., the number of height levels used, the use of vertical viscosity). We therefore choose the 1D wave parameterization scheme parameters to match the case of the 3D model with no extratropical wave forcing, $\Phi_0 = 0$. However, even in this absence of extratropical wave forcing, there is still some equatorial upwelling in the 3D model due to the radiative cycle, and this must be included in the 1D model for the behavior to match. Then, equatorial upwelling is put into the 1D model of comparable magnitude to that seen in the 3D model with extratropical wave forcing, and the results of the 1D model compared to those of the 3D model.

In the 3D model with no QBO and no extratropical wave forcing, there is a weak semiannual oscillation in the upwelling, but to a first approximation we model this by time-constant upwelling (since, when extratropical wave driving is added to the 3D model, the semiannual component is negligible in comparison to the annual component). The variation of upwelling with height is close to being exponential (apart from an anomaly at the lowest level, which is due to the lower boundary condition). This upwelling is here approximated in the 1D model by

$$w_c = 10^{-4} \exp \left( \frac{z - 37 \text{ km}}{10 \text{ km}} \right) \text{ m s}^{-1}. \quad (7)$$

The parameterized wave phase speed is kept as $c = 20 \text{ m s}^{-1}$ as in the 3D model. The vertical viscosity $\kappa$ is chosen to give QBO amplitude corresponding to that of the 3D model (and to a lesser extent, to give a reasonable structure to the QBO so that changes and gradients are not too sharp). We take $\kappa = 0.473 \text{ m}^2 \text{ s}^{-1}$, which gives a QBO amplitude approximately equal to that of the phase speed, while at the same time a similar vertical structure to the 3D model.

The wave forcing value $F_0$ in the 1D model is chosen to give the same period of oscillation as the 3D model in the case of no extratropical wave forcing (but with a radiative cycle). For the 3D model with $F_0 = 1.07$ and $\Phi_0 = 0$, the oscillation has period 1.757 yr. With radiative upwelling in the 1D model as defined above, taking $F_0 = 2.085$ in the 1D model gives period 1.758 yr.

The value of $L$ for the QBO upwelling in the 1D model is then chosen so as to give a QBO upwelling of the same order and QBO asymmetry as similar as possible to that seen in the 3D model with $F_0 = 1.07$ and $\Phi_0 = 0$. Matching up the QBO upwelling and the QBO asymmetry gives slightly different values of $L$, which average out to 500 km. This is the same value as that suggested by Dunkerton (1982).

Finally we change the upwelling parameters for the 1D model $w_c$ and $w_c\omega$ to match the upwelling seen in the 3D model with no QBO and $\Phi_0 = 285$ m, that is, the constant and annually varying upwelling due to both extratropical wave driving and radiative heating. The climatological upwelling from the 3D model has a strong annual cycle, with the strongest upwelling shortly after midwinter and weakest upwelling after. The height variation is again approximately exponential. We approximate these by using

$$w_c = 5.8 \times 10^{-4} \left[ 0.2 + 0.8 \exp \left( \frac{z - 37}{10} \right) \right], \quad (8)$$

$$w_c\omega = 4.2 \times 10^{-4} \left[ 0.2 + 0.8 \exp \left( \frac{z - 37}{10} \right) \right]. \quad (9)$$

With these upwelling values, the oscillation has a period of 2.28 yr, compared to 2.37 yr for the 3D model. Considering the approximations taken here, the similarity between the periods of 1D model and the 3D model is good.

The phase alignment is strongest at height 17 km. (The phase alignment at this height is shown in Fig. 12.) The $\pi = 0_{\text{we}}$ phase peaks around November–January, and the $\pi = 0_{\text{we}}$ phase peaks around October–February. It is somewhat weaker than the phase alignment seen in the 3D model, although the smaller number of years in the 3D model simulations introduces uncertainties. The $\pi = 0_{\text{we}}$ phase alignment is again significantly stronger than for the $\pi = 0_{\text{we}}$ phase, as was seen in the 3D model.

For comparison with the height level giving strongest phase alignment in the 3D simulations, the phase alignment at height 25.4 km is shown in Fig. 11. There is
7. Conclusions and limitations

We have investigated the issue of phase alignment of the tropical QBO in the annual cycle, using Singapore radiosondes and NCEP reanalysis data, a 3D mechanistic model, and a 1D equatorial model. The Singapore radiosondes and NCEP data show strong phase alignment, particularly in the $\pi = 0_{\text{ew}}$ windline, similar to that found by Dunkerton (1990). The 3D model also gives rise to strong phase alignment; this can be seen in various ways. Specifically, it occurs as phase alignment of a 2-yr QBO, as preference for 2-yr period for QBOs with a period close to 2 yr and as a phase alignment (again, particularly in the $\pi = 0_{\text{ew}}$ windline) for a QBO of noninteger period. It is hypothesized that the phase alignment is due to a large extent to the annual cycle in equatorial upwelling. This hypothesis is supported by the 1D equatorial model of a QBO modulated by annually varying upwelling, although the 1D model QBO has weaker phase alignment at middle QBO heights than that seen in the 3D model. The 1D model also shows a preference for a 2-yr period when the annual cycle in upwelling is included.

The mechanism identified here can be regarded as a generic behavior of a nonlinear system similar to those such as parametric excitation or frequency locking described, for example, by Glendinning (1994). In fact none of the well-known types of behavior quite match that identified here. In the QBO case, one has a nonlinear oscillator (arising from the basic wave–mean flow interaction mechanism) modulated by an external time-periodic signal (the annually varying upwelling). The phenomenon illustrated in Figs. 6 and 10 is that for an appropriate range of the natural (nonlinearly determined) frequency, the nonlinear oscillator tunes itself to a subharmonic of the modulation frequency (half the natural frequency in the case of the 2-yr period). Analytical calculations in heuristic mathematical models suggest that the frequency intervals where this would occur for two-fifths or one-third of the natural frequency (corresponding to 2.5- or 3-yr periods) are much narrower, consistent with the difficulty of identifying such cases from our numerical results. The reason for this is that higher-order nonlinearities are required to obtain the self-tuning effect.

One obvious limitation of this study is the way in which the QBO is forced in the model. The parameterization scheme described in Eq. (2) does not necessarily correspond exactly to the wave forcing of the observed QBO [in particular, the possibility of latitudinally propagating planetary waves providing some of the QBO forcing, as investigated by Dunkerton (1983), is not considered here]. However, an investigation of different QBO forcing mechanisms lies beyond the scope of this study.

Another question that has not been addressed here is that of the vertical structure of the phase alignment, and any implications on phase alignment of the QBO stall-
ings mentioned at the end of section 3. The best scope for this is through some kind of EOF analysis (Wallace et al. 1993) or nonlinear principal component analysis (Hamilton and Hsieh 2002), with the latter looking particularly promising. It is interesting that both these papers argue that the clearest signal of seasonal modulation is in the rate of change of phase, rather than the actual phase. Nonetheless, the results of both papers are broadly consistent with the mechanism we investigate here, in that the rate of change of phase is small in the late Northern Hemisphere winter, when the upwelling rate is expected to be large. The results of the two papers differ in that Hamilton and Hsieh (2002) show a stronger semiannual signal, with a secondary minimum in rate of change of phase in Northern Hemisphere autumn (or Southern Hemisphere spring). It should not be forgotten that while the upwelling velocity in the Tropics (and hence the temperatures) are dominated by an annual cycle in the lower stratosphere, a semiannual cycle dominates in the midstratosphere (Reid 1994; Rosenlof 1995). Thus it may be that the semiannual cycle in upwelling in midstratosphere (rather than any other aspect of the semiannual oscillation) is responsible for the modulation found by Hamilton and Hsieh (2002). This and other aspects of the height variation of the seasonal modulation merit further study.

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