Seasonal Variation of the Quasi-Biennial Oscillation Descent

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Key Points:

- The Quasi-Biennial Oscillation (QBO) descent rates quantified using EOF analysis.
- Semi-annual signal found in descent rates linked to global circulation.
- Semi-annual slowing of QBO descent implies fewer wind transitions at those times.

Abstract

This study examines variations through the year in the rate of descent of the Quasi-Biennial Oscillation (QBO) wind in the tropical lower stratosphere. The work is based on the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) multi-year global reanalysis. A 10-member ensemble of free-running atmospheric simulations using the Global Earth Observing System (GEOS) atmospheric general circulation model is also examined. The QBO winds are decomposed into two orthogonal modes that describe amplitude and phase propagation. This reveals a semi-annual signal in descent rate, with slow descent at times of large middle-latitude planetary wave activity, suggesting that this wave activity influences equatorial vertical velocity. This result also explains the suppression of QBO wind transitions during active wave times. Results also show a variation in descent speed when plotted against QBO phase. These results provide a baseline of QBO behavior for future QBO modeling.

Plain Language Summary

The Quasi-Biennial Oscillation dominates the lower stratospheric equatorial wind variability, with alternating descending easterly and westerly wind regimes. While the QBO has a dominant 28-month recurrence, prior studies have linked some of the variability to phase locking to the annual cycle. Thus study uses a multi-year global reanalysis to isolate impacts of the annual cycle on the QBO, demonstrating that slow descent rates are associated with times of large middle-latitude planetary wave activity, which can influence equatorial vertical velocity. This result explains the suppression of QBO wind transitions during the seasons when dynamical activity in the middle latitudes is largest. It provides a baseline of QBO behavior that is invaluable for, e.g., studies of QBO impacts and for projections of QBO changes under future climate scenarios.

1 Introduction

The Quasi-Biennial Oscillation (QBO) dominates the tropical lower stratosphere with East-West winds that reverse direction, repeating approximately every 28-29 months (Baldwin et al., 2001). The winds change direction first at upper levels (~10 hPa or lower pressures) before descending to the tropopause (~100 hPa), with the necessary zonal momentum being supplied by the damping of vertically propagating global- and small-scale waves (Lindzen and Holton, 1968; Holton and Lindzen, 1972). Variations in the forcing waves and background mean circulation, coupled with the changing QBO wind profile, contribute to the observed irregular QBO period. The QBO descent is known to stall at times creating a longer cycle (Dunkerton, 1990; Fraedrich et al., 1993; Kinnersley and Pawson, 1996; Hampson and Haynes, 2004; Rajendran et al., 2018) and wind direction transitions have been documented to occur more frequently near the equinoxes (Baldwin et al., 2001; Newman et al., 2016).

The slowing or "stalling" of the QBO descent and its relation to the annual cycle has been observed and modeled in the past. Dunkerton (1990) noted an annual tendency for QBO stalling with a weaker semi-annual stall signal seen in the upper levels. Wallace et al. (1993) using a technique based on EOFs (Empirical Orthogonal Functions) found an annual signal in the QBO descent rate. Hamilton and Hsieh (2002) showed the QBO descent slows significantly during times of active planetary wave activity, and hence times of increased upward equatorial motion, in both the Northern and Southern Hemispheres. Modeling studies (Kinnersley and Pawson, 1996; Hampson and Haynes, 2004) have identified equatorial mean vertical motions driven by extra-tropical planetary waves as capable of slowing the QBO descent during times of active planetary waves and, by including mean equatorial vertical motion as a factor in a mechanistic QBO model, Rajendran et al. (2018) reproduced the synchronization of the QBO with the annual cycle.

An Empirical Orthogonal Function (EOF) analysis of the QBO (Wallace et al., 1993) is used to examine the variations in the QBO descent rate from 1980-2018 both as a function of season and as a function of the QBO vertical structure or phase in EOF space. Differences from prior studies based on sparse observations include the use of a reanalysis data set which allows for: 1) zonal averages in place of station data, 2) daily QBO analysis in place of monthly means, and 3) higher vertical resolution than past studies. The goal is to tie together some long-standing features of the QBO descent rate from a uniform perspective. Documenting the observed QBO descent rate can then form a basis for future improvements in QBO modeling and forecasting.

2 Analyses and Method

The global, gridded, zonal and meridional winds and temperatures are provided by the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017), an ongoing reanalysis beginning with the year 1980. Based on global observations as well as a general circulation model containing a QBO (Molod et al., 2015), the MERRA-2 QBO winds match well with the available radiosonde observations. Detailed descriptions of the representation of the QBO in MERRA-2 are found in Coy et al. (2016) and Kawatani et al. (2016).

For this study the MERRA-2 zonal winds and temperatures (GMAO, 2015) were used to compute meridional heat flux (v'T') averaged daily and zonally averaged on model levels, in order to compute daily residual mean vertical wind fields (w*, Andrews et al., page 128). The zonal mean fields were then averaged between 10ºS and 10ºN. The calculated residual vertical winds were smoothed in time using a 30-day boxcar smoother to eliminate the day-to-day variability, while the meridional heat fluxes were smoothed in time using a 15-day boxcar smoother for presentation purposes. Positive (negative) heat fluxes correspond to upward wave activity propagation in the Northern (Southern) Hemisphere (NH/SH) so the negative of the heat flux is plotted for the SH.

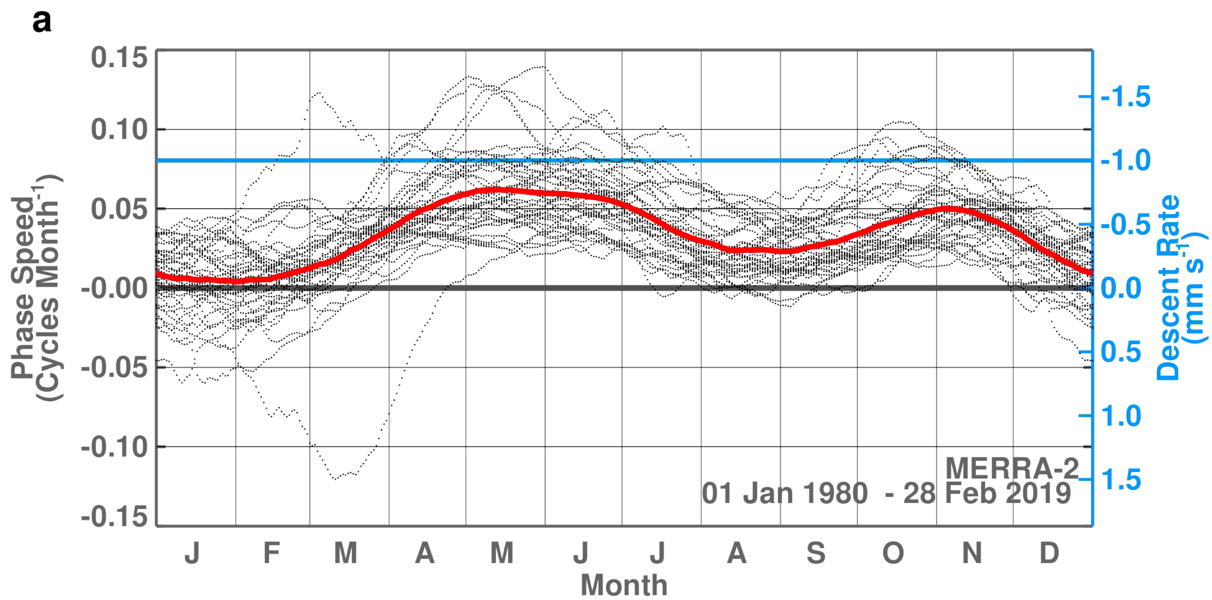
The EOF analysis follows Wallace (1993). A correlation matrix was formed from the daily equatorial zonal-mean zonal winds between 100 and 10 hPa (14 model levels), yielding a 14x14 matrix that was then solved for the 14 EOF vertical structure functions. As in Wallace (1993), ~95% of the QBO variance is explained by the first two EOFs. These two EOFs, with approximately equal variance, are needed to represent the downward propagating QBO signal.

The two EOF's can also be interpreted in a polar plane as an amplitude and phase. Here the time derivative of the phase will be taken as the phase speed, or descent rate, of the QBO.

A corresponding EOF analysis was performed for the ten-member "M2-AMIP" (MERRA-2 – Atmospheric Model Intercomparison Project) ensemble (Collow et al., 2017). These 37-year (1980-2017) GEOS GCM runs use the same the GEOS model from the MERRA-2 analyses. These EOF analyses used monthly averaged equatorial zonal winds saved on seven pressure levels between 100 and 10 hPa. The descent phase speed is based on monthly changes in representation of the zonal-mean zonal wind by the first two EOFs.

3 Results

The MERRA-2 QBO EOF based rate of descent consistently slows near January, February and August, September (Fig. 1a). The mean descent rate value of .034 QBO cycles/month corresponds to the observed 29-month period, however the seasonal variation of descent is substantial with the average value (red curve) ranging from .004 to .062 cycles/month, corresponding to periods of 243-16 months. Some of the descent phase speeds attain large values for individual years. The highest value, 0.14 cycles/month, if sustained, would produce a QBO cycle of only 7.2 months. The large negative values seen in February through April occurred during 2016 and are a signature of the QBO disruption (Newman et al., 2016; Osprey et al, 2016), a time when the vertical structure of the equatorial winds poorly fit the first two EOFs (Tweedy et al., 2017).



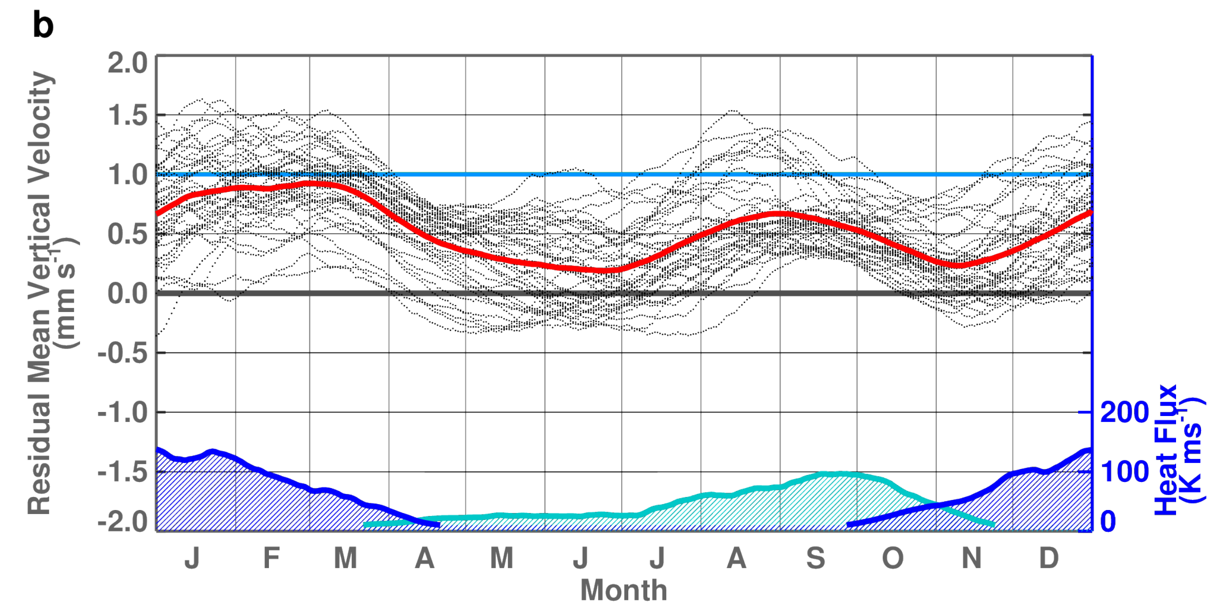


Figure 1. a) The descent phase speed of the QBO (cycles month^{-1}) and b) the 10-hPa zonal mean equatorial vertical velocity (mm s^{-1}) as a function of time of year for Jan 1980 through Feb 2019. The red curves denote the daily average values over all the years. Also plotted in b) are the 60ºN (blue) and the negative of the 60ºS (cyan) 10-hPa meridional heat flux (K m s^{-1}) averaged over the same time period. The light blue horizontal line denotes the 1 mm s^{-1} value. All fields are derived from MERRA-2 analyses.

The semi-annual signal seen in the descent rate can be related to the equatorial vertical motion and middle-latitude planetary wave activity. For example, the 10 hPa equatorial mean residual vertical velocity (Fig. 1b) shows increased upward motion occurring during times when the QBO descent in Fig. 1a is slowed. This semiannual signal in vertical motion is in turn closely related to the middle-latitude planetary wave activity, as characterized, for example, by the 10 hPa meridional heat flux at 60º latitude North and South (Fig. 1b). Wave activity supports the mean Equator to pole Brewer-Dobson circulation (Butchart, 2014), increasing the upward motion in the Tropics during times of strong wave activity. Times with strong wave activity in Fig. 1b correspond closely with times of increased upward tropical motion and slowing of the QBO descent. There are well-known hemispheric asymmetries in the middle latitude wave forcing strength and timing with stronger Northern Hemisphere (NH) than Southern Hemisphere (SH) wave forcing and a late winter, early fall SH maximum in contrast to a mid-winter NH maximum. These hemispheric asymmetries are also present in the QBO descent (Fig. 1a) which shows a lower minimum during NH winter (December-February) than during the SH late winter, early spring (August-September).

The speed of the QBO descent can be scaled as a vertical velocity and compared with the residual mean vertical velocity by assuming that each phase of the QBO descends over the distance between 10 and 100 hPa during one complete QBO cycle (Fig. 1a, right axis). This average descent speed, ~0.4 mm/s, has the same magnitude as the average residual mean vertical velocity at 10 hPa (Fig. 1b, ~0.5 mm/s) and the monthly variations are also of approximate the same order of magnitude as the 10 hPa residual mean vertical velocity. These similar values support the idea that the mean residual vertical velocity strongly influences the descent speed of the QBO.

The same QBO descent phase speeds can also be examined as a function of the QBO phase instead of the annual cycle (Fig. 2a). For understanding the EOF vertical structures, the average equatorial winds are also plotted as a function of QBO phase (Fig. 2b). The QBO descent slows during QBO phases with strong vertical wind shears near 30 hPa (phases of 0º and 180º in Fig. 2), though the mean values have less variation than in the annual cycle (Fig. 1a). However, the distribution (yellow histogram plot) shows more points (days) near those slow descent QBO phases. This distribution describes the “foot” that shows in QBO time vs height contour sections where the descent slows significantly, spending a longer time during those strong wind shear phases, especially during the easterly over westerly wind phase (Fraedrich et al., 1993).

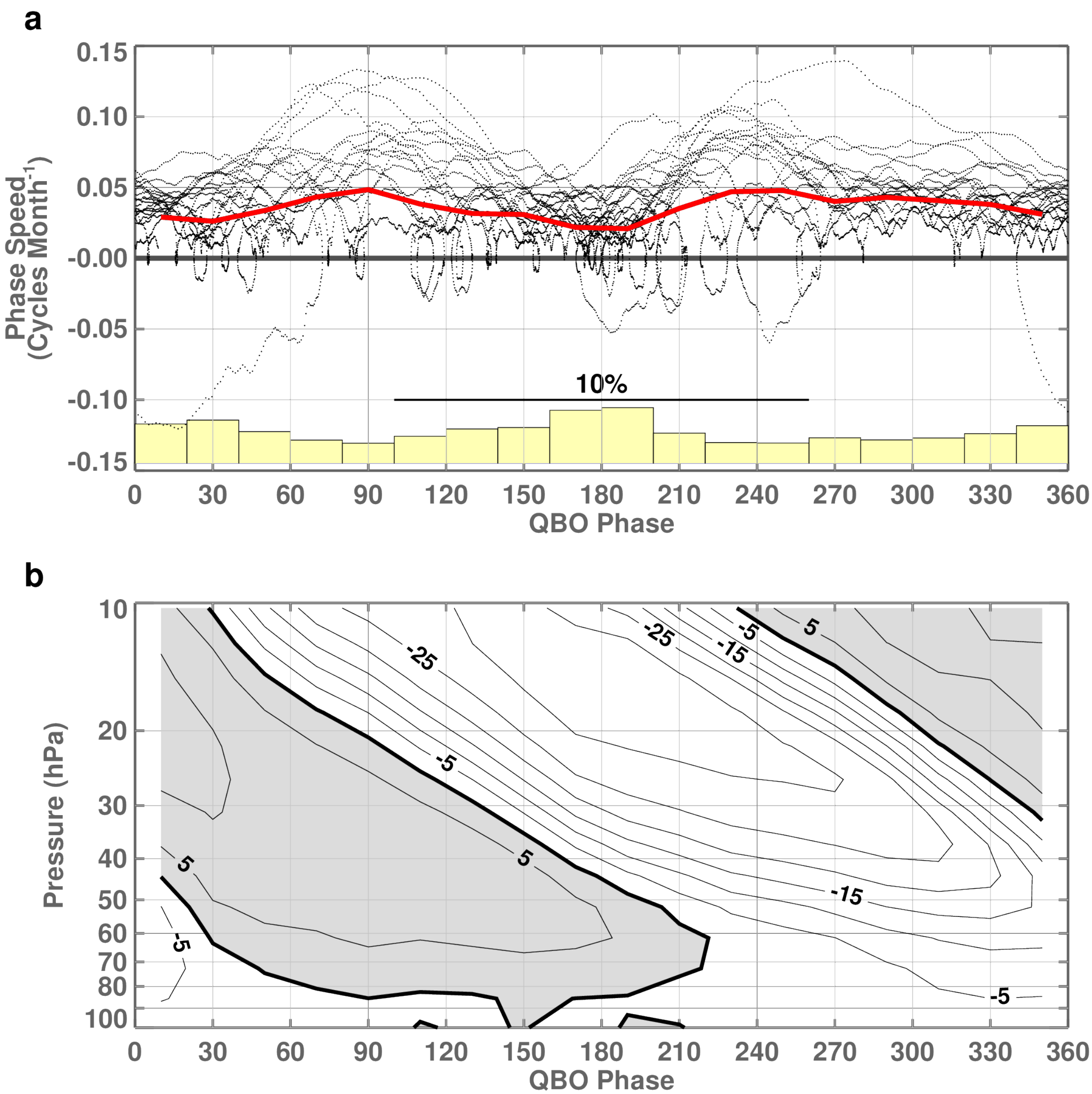


Figure 2. a) The descent phase speed of the QBO (cycles month^{-1}) as a function of QBO phase for Jan 1980 through Feb 2019 and b) the QBO zonal mean, zonal wind (m s^{-1}) as function of QBO phase (degrees) and pressure (hPa). The red curve in a) denotes the mean of the descent phase speeds. Also plotted in a) is the histogram of the descent phase speeds with respect to QBO phase (filled yellow regions).

Averaging all the slow and fast descent rate profiles separately highlights the difference between the slow and fast descent QBO structure (Fig. 3). These are unrealistic QBO time vs pressure profiles as the fast and slow rates change faster than the 29-month QBO cycle according to the annual variability. Nevertheless, the slow QBO descent rate (Fig. 3a) is seen to be associated with the lingering of the westerlies in the lower stratosphere while the fast QBO descent rate (Fig. 3b) yields a more uniform QBO pattern.

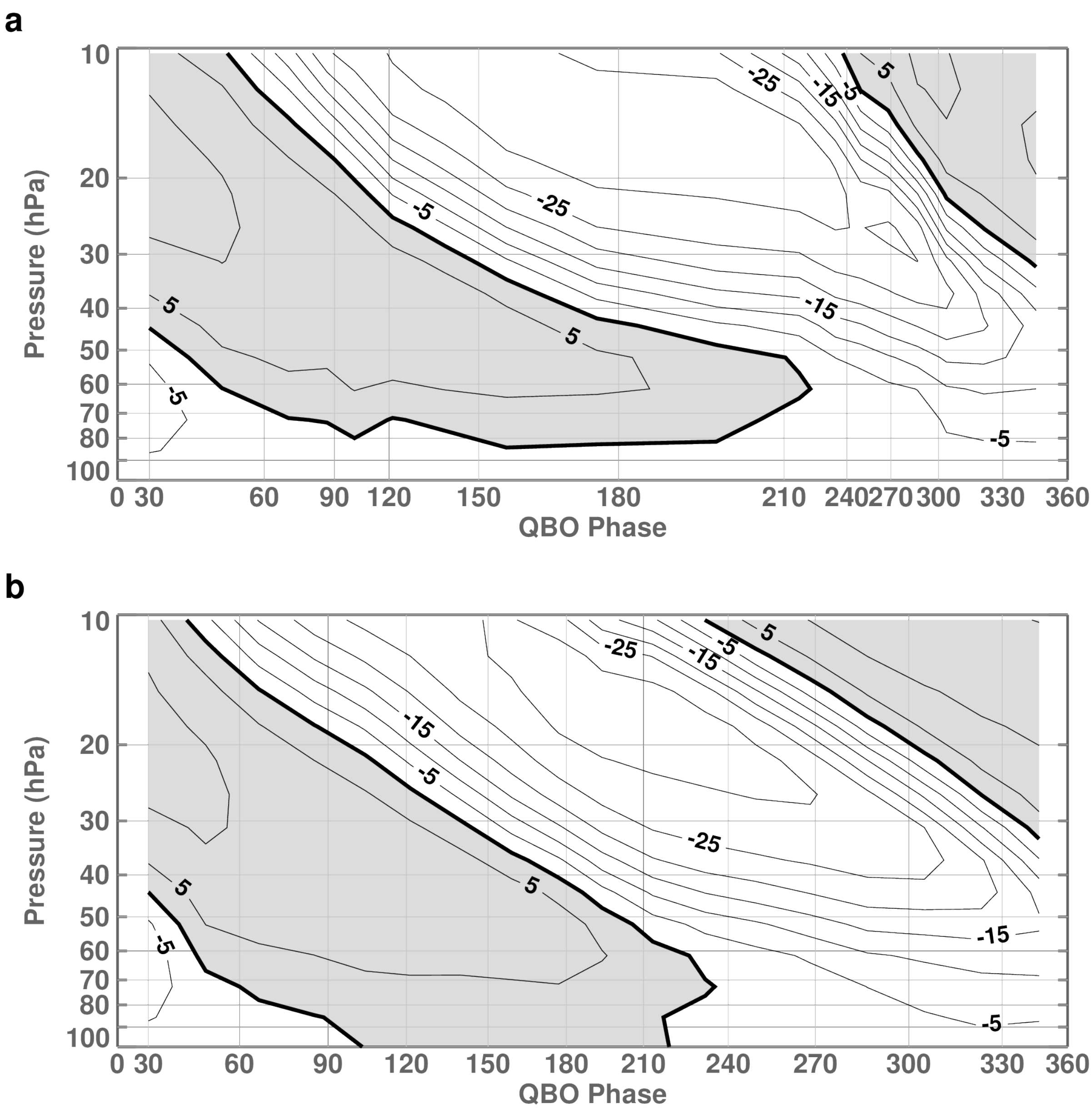


Figure 3. The average of the MERRA-2 equatorial winds composited for a) slower and b) faster than average descent phase speed of the QBO (cycles month^{-1}) as a function of QBO phase for Jan 1980 through Feb 2019. The phase coordinate is adjusted based on the time (number of days) spent in that phase.

While the QBO descent rate is related to the annual cycle and the QBO phase as shown above, both Wallace et al. (1993) and Hamilton and Hsieh (2002) also examined the relation of the

QBO phase to the annual cycle. Plotting QBO phase against time of year (Fig. 4) reveals some tendency for the active planetary wave seasons to have a phase near 180º, easterlies over westerlies. This is especially apparent during August-September, when the SH planetary waves are most active. However, there is considerable spread in the phases that can occur during any time of year and as Wallace et al. (1993) concluded, more years are probably needed to fully characterized the distribution. (Note that Wallace et al. used station data for 1950-1992, while the present study uses analyses for 1980-2019).The seasonal slowing of the QBO descent (phase slopes near or less than zero) during December-February and August-September can also be seen in Fig. 4. The slowing can occur during any phase of the QBO but is stronger during phases near 180º, consistent with Fig. 2a. Note especially the strong slowing during the recent strong planetary wave times during the NH winter of 2018 (Karpechko et al., 2018) and SH late winter to early fall of 2019 (Hendon et al., 2019).

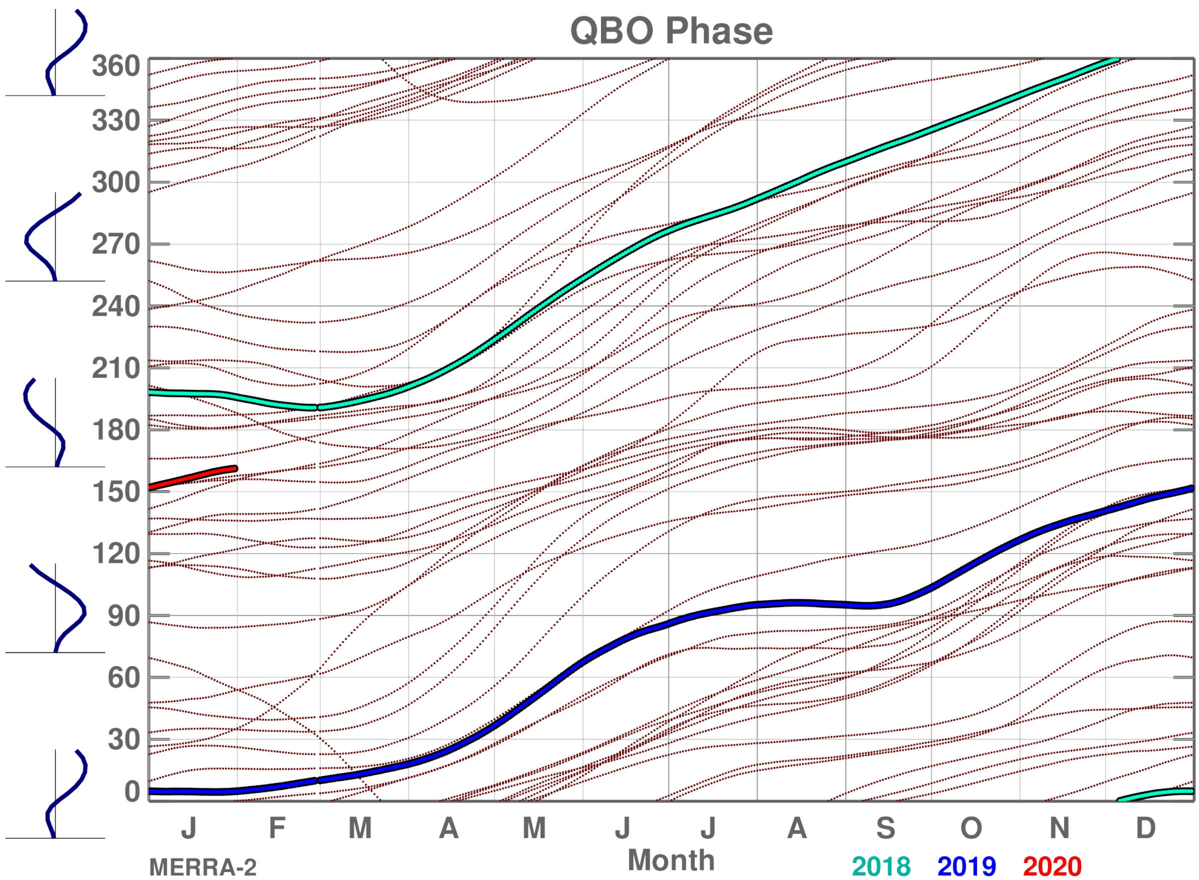


Figure 4. The phase of the QBO (cycle) as a function of time of year for the years from 1 January 1980 through 28 February 2019. Recent years, 2018, 2019, and 2020, are highlighted as green, blue, and red respectively. The EOF vertical structures associated with 0, 90, 180, 270, and 360º phases are plotted along the left axis.

The QBO in the MERRA-2 analyses is forced in large part by parameterized non-orographic gravity waves (NOGW), but relies on the wind measurements to keep it in phase with observations (Coy et al., 2017). Since the NOGW parameterization forcing used in MERRA-2 is independent of time or the current atmospheric state, it seems unlikely that the unresolved NOGWs can be be playing a major role in the annual signal in QBO descent rate. EOF analyses from the global model runs (Fig. 5) show annual variation patterns in their QBO descent rate that are similar to those in the assimilated data (Fig.1a), once again suggesting that the mid-latitude wave induced tropical lifting is main mechanism slowing the QBO descent. The similar annual variation patterns in both model and data assimilation output rules out the possibility that the data assimilation process is somehow responsible for the descent speed variability.

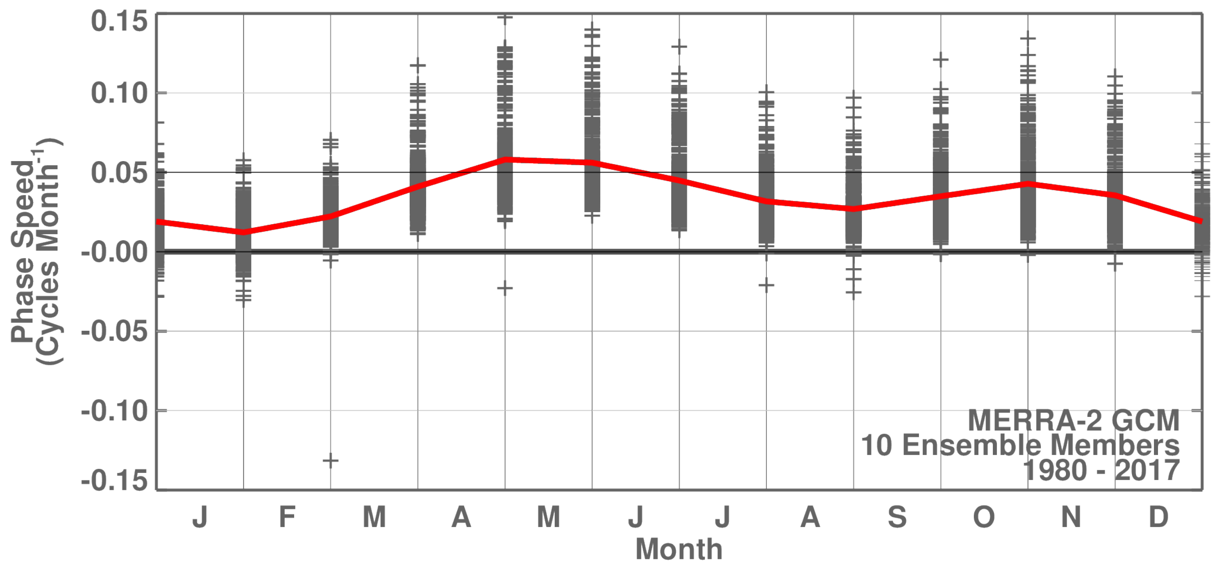


Figure 5. The descent phase speed of the QBO (cycles month^{-1}) as a function of time of year for ten ensemble MERRA-2 model only runs for Jan 1980 through Dec 2017 base on monthly averaged output on seven pressure levels. The red curve denote the monthly averaged values over all the ensembles and years.

4 Conclusions

These results document the significant slowing of the QBO descent during times of strong seasonal middle latitude planetary wave activity. The use of a global data assimilation system provides a new perspective over past studies based on station data by enabling more detailed time and space analysis of the QBO and an exact computation of vertical velocity in the underlying model. Examination of the 10-hPa equatorial vertical velocity and middle-latitude meridional heat flux support the hypothesis that the planetary waves induce enhanced uplifting in the Tropics thereby slowing the QBO descent at those times. The QBO descent speed (Fig. 1a) also captures the known asymmetry in wave activity between the two hemispheres, with the most dramatic slowing occurring during NH winter. The magnitude of the semi-annual variation in QBO descent speed is approximately equal to the residual mean vertical velocity perturbation (Fig. 1), since the QBO shear zone typically descends ~16 km (10 to 100 hPa) in approximately half a QBO period (~14 months) for a velocity of ~0.4 mm/s. Thus, these similar magnitudes also support the uplift hypothesis.

As noted previously (e.g., Hamilton and Hsieh, 2002) the annual pattern in QBO descent variability (Fig. 1a) at least partly explains the long-noted pattern in wind direction transitions months (for example, Baldwin et al., 2001, Newman et al., 2016) where the transitions occur more frequently during the equinoctal seasons. Since the QBO is often stalled, or changing more slowly, during Jan-Feb and Aug-Sep, few transitions would be expected during those times. Thus this slowing in QBO descent provides a simple model for identifying the months when wind transitions would be most likely.

The results also illustrate the tendency of the QBO to found more frequently in some phases (Fig. 2a). In EOF space the QBO phase occurs most frequently, or stalls, during times of strong wind shear near 30 hPa. This tendency to stall is strongest when easterlies are over westerlies and is the representation in EOF space of the tendency of low-level westerlies to persist, forming a foot-like low level westerly feature in conventional time vs height zonal wind plots (Fig. 3a). This feature, while documented here, requires further study to fully understand the underlining dynamics, however it may prove to be that a particular QBO wind pattern feeds back more effectively on the planetary waves, encouraging the waves to further increase the tropical uplift. This type of feedback may be related to the Holton-Tan relationship between the QBO and the mid-latitude stratosphere (Holton and Tan, 1980).

While the model and data assimilation QBO descent speed annual patterns are similar (Figs. 1a and 5), there are some differences. In particular, the slowing of the QBO descent speed near the equinoxes appears to be less pronounced in the model than in the reanalysis. This may indicate that the planetary waves are somewhat weaker in the model and not creating as much tropical upwelling as in the real atmosphere. Thus QBO descent speeds may be a useful diagnostic of the global circulation induced by wave driving.

These results highlight the continued usefulness of EOF-based analysis of the QBO. While EOF-based results depend to some extent on the chosen vertical domain and levels, the features presented here, based on a reanalysis and an ensemble of model simulations, should be identifiable in other QBO reanalyses and simulations. In addition, evaluation of the seasonal dependence of the QBO descent should be a useful diagnostic not only for the QBO but also for the required middle-latitude wave activity and the resulting tropical response. Moreover, the tendency of the QBO to persist in certain phases should be useful as a QBO structure diagnostic and provide guidance for improved understanding of the QBO dynamics.

Acknowledgments

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