Quasi-biennial modulation of the southern hemisphere stratospheric polar vortex

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Abstract. Observations reveal that the wintertime southern hemisphere stratospheric polar vortex is modulated by the phase of the equatorial quasi-biennial oscillation (QBO). The high-latitude southern stratosphere is shown to be slightly colder throughout the winter, and the final warming occurs later, when the QBO is in its west phase. During May–October, the modulation of winds by the QBO is confined to midlatitudes, at the edge of the polar vortex. The difference between west and east phase composites of zonal mean wind during November, at the time of the final warming in the southern hemisphere, exceeded 14 ms^{-1}. This difference is very similar to that in January in the northern hemisphere. While northern hemisphere QBO effects are optimized using equatorial winds near 40 hPa, southern hemisphere effects are best seen using ~25 hPa winds.

Introduction

Both observational and modeling studies have established that the quasi-biennial oscillation (QBO) in equatorial stratospheric winds has a substantial effect on the wintertime northern hemisphere polar vortex. *Angell and Korshover* [1962] showed that a temperature QBO existed in the northern midlatitude stratosphere, while *Angell and Korshover* [1964, 1967] explored a temperature QBO at middle to high latitudes in both hemispheres. *Holton and Tan* [1980] documented, using data for the period 1962–1977, that when the equatorial winds at 50 hPa are easterly, the northern polar vortex is more disturbed by waves, is warmer, and disruption of the vortex by sudden stratospheric warmings is more likely. The accepted explanation for this effect involves the propagation of quasi-stationary planetary-scale waves, which originate in the troposphere and propagate vertically and meridionally. Their propagation and interaction with the mean flow depends on the latitude-height structure of the zonal mean wind, and in particular the position of the "zero wind line" separating easterlies from westerlies [*O'Sullivan and Dunkerton*, 1994]. The phase of the QBO affects both the position of the zero wind line and the structure of the zonal-mean wind field. When the equatorial winds are easterly, planetary waves tend to propagate higher and more poleward than when the QBO is in its west phase. The influence of the QBO on the northern vortex is relatively large because planetary-wave amplitudes are often, but not always, large enough to disrupt the vortex in major stratospheric warmings. The QBO appears to modulate the effectiveness of the planetary waves' influence on the strength of the vortex. *Van Loon and Labitzke* [1987], *Dunkerton and Baldwin* [1991], and *Baldwin and Dunkerton* [1991] further documented the relationship between the QBO and the northern winter vortex.

The situation in the southern hemisphere is different, with relatively small planetary-wave amplitudes. Major midwinter warmings in the middle stratosphere do not occur, and consequently the interannual variability of the wintertime southern vortex is smaller; the vortex is much stronger, colder, and longer-lived than in the northern hemisphere. Observationally, the establishment of a connection between the QBO and the southern vortex is made difficult by a paucity of data prior to satellite observations in the late 1970s. Polar station radiosonde observations were inadequate to establish even monthly averages of zonal-mean wind or temperature. The southern hemisphere influence of the QBO has been examined by several authors [*Garcia and Solomon*, 1987; *Lait et al.*, 1989; *Angell*, 1990], primarily in conjunction with the ozone hole. Garcia and Solomon noted a QBO in the minimum vortex temperature in the 200–50 hPa layer during October, while *Lait et al.* [1989] found that the temperature QBO was strongest at the South Pole. *Newman and Randel* [1988] found a quasi-biennial modulation of the September–October wave-1 eddy heat flux in middle southern latitudes. *Randel and Cobb* [1994] used satellite data for the period 1979–1992 to document that there was quasi-biennial modulation of temperature (as measured by satellite retrievals in the 150–50 hPa layer) in the southern vortex during late spring. During midwinter the modulation was confined to low latitudes, but at the end of winter (November) polar temperatures were modulated by the phase of the QBO. In this paper we examine, using zonal-mean wind, the seasonal development and vertical extent of the QBO's influence on the southern vortex with a comparison to the northern hemisphere.

Data and Processing

Our global data consist of daily National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center, or NMC) 1200 UTC heights and temperatures. For the period September 24, 1978 to May 11, 1996, these data are available globally at the levels 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, and 1 hPa. The data set is archived on a 5° × 4° longitude/latitude grid. The data were subject to quality control to remove erroneous grids. Single missing levels were interpolated vertically. All remaining missing data were linearly interpolated in time. Horizontal wind components were calculated using the linear balance method [*Robinson*, 1986; *Hitchman et al.*, 1987; *Randel*, 1987].

Comparison with the newer NCEP reanalyzed data (which include wind components but extend to only 10 hPa) shows that the two datasets are very similar, including the extratropical QBO composite. Neither dataset captures the amplitude of the tropical QBO as seen in radiosonde data, but the tropical

Paper number 98GL02445.
0094-8534/98/98GL-02445$05.00

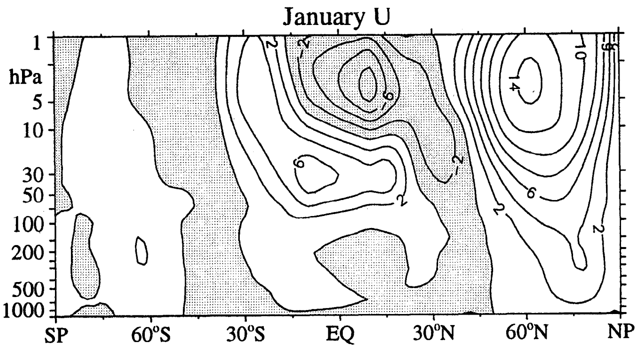

Figure 1. January latitude-height zonal-mean wind difference between the average of all years with west QBO and those with east QBO. The phase of the QBO is defined using u^* with $\phi=0°$ (see text), which is nearly equivalent to using 40-hPa equatorial winds. The contour interval is 2 ms^{-1} and negative values are shaded.

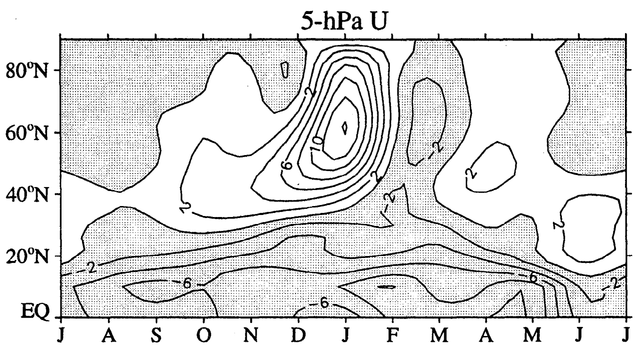

Figure 2. Northern hemisphere 5-hPa month-latitude zonal-mean wind difference between the average of all years with west QBO and those with east QBO. The phase of the QBO is defined using u^* with $\phi=0°$, as in Figure 1. The contour interval is 2 ms^{-1} and negative values are shaded.

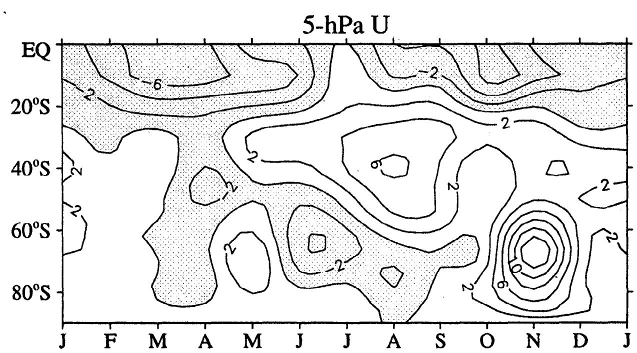

Figure 3. Southern hemisphere 5-hPa month-latitude zonal-mean wind difference between the average of all years with west QBO and those with east QBO. The calculation is as in Figure 2, except the phase of the QBO is defined using u^* with $\phi=50°$, which is nearly equivalent to using 25 hPa equatorial winds.

QBO in reanalyzed data is about twice as large as that in the balance wind calculation shown below. We use radiosonde observations to define vertical empirical orthogonal functions (EOFs) of the QBO and to calculate the QBO phase, as described next.

Definition of the QBO phase

Radiosonde observations of stratospheric equatorial winds are available monthly since 1956 at each of the levels 70, 50, 40,

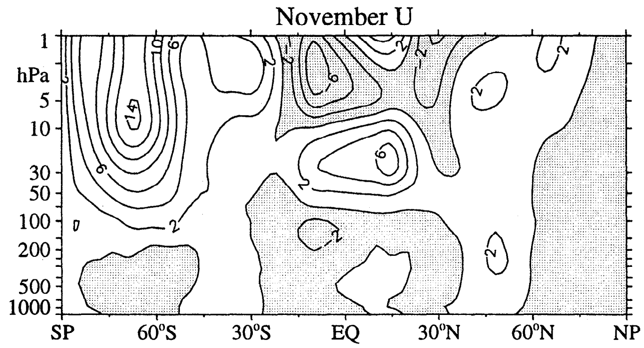

Figure 4. November latitude-height zonal-mean wind difference. The calculation is as in Figure 1 except the phase of the QBO is defined using u^* with $\phi=50°$, as in Figure 3.

30, 20, 15, and 10 hPa. Traditionally, one of these levels or some combination of levels has been used to define the QBO or "phase" of the QBO (east or west) during any given month (e.g. *Holton and Tan*, 1980; *Labitzke and van Loon*, 1988; *Dunkerton and Baldwin*, 1991). The magnitude of composites or correlations involving extratropical fields depends on the exact level chosen to define the QBO. In the northern hemisphere, the strongest extratropical signals are obtained using a level near 40 hPa; the magnitude of the southern hemisphere response appears to be maximized using a slightly higher level, such as 20–30 hPa. Since the QBO consists of downward propagating easterly and westerly wind regimes, results obtained using radiosonde data at 10 hPa will be of the opposite sign to those which employ a much lower level, such as 70 hPa. *Randel et al.* [1995], recognizing that the extratropics do not respond dynamically to one specific equatorial wind level, used a linear combination of equatorial data levels to maximize the extratropical signal in ozone.

The phase of the QBO in the 70–10 hPa layer can be represented using a single time series by combining the first two EOFs of monthly equatorial wind observations. *Wallace et al.* [1993] used deseasoned equatorial wind observations at 7 levels from 1956–1990 to calculate 7 EOFs of the QBO, and their associated principal component time series. Remarkably, over 95% of the variance of the equatorial wind was accounted for by the first two EOFs. Their Figure 3 illustrates the vertical structure of the first two modes, with the first mode of opposite sign at 70 and 10 hPa, passing through zero between 40 and 30 hPa. The second mode exhibits amplitude minima at 70 and 10 hPa, with its peak at 40–30 hPa.

The phase of the QBO may then be defined using the principal component time series of the first two EOFs, a and b. Figure 5 of *Wallace et al.* [1993] illustrates that a graph of a vs. b traces out a nearly circular pattern in time. The phase of the QBO, ψ, may be defined as the angular position along the path,

$$\psi=\arctan(b/a) + \phi$$

where ϕ is an arbitrary phase adjustment. The amplitude is given by $c=\sqrt{(a^2+b^2)}$, and we define the QBO time series as

$$u^*=c \times \sin(\psi).$$

The single time series, u^*, may be used in place of a single level of observed wind when calculating composites or correlations. Adjustment by ϕ corresponds closely to varying the pressure level used to define the QBO.

We calculated EOFs of equatorial wind using unfiltered monthly equatorial wind data at seven levels for the period

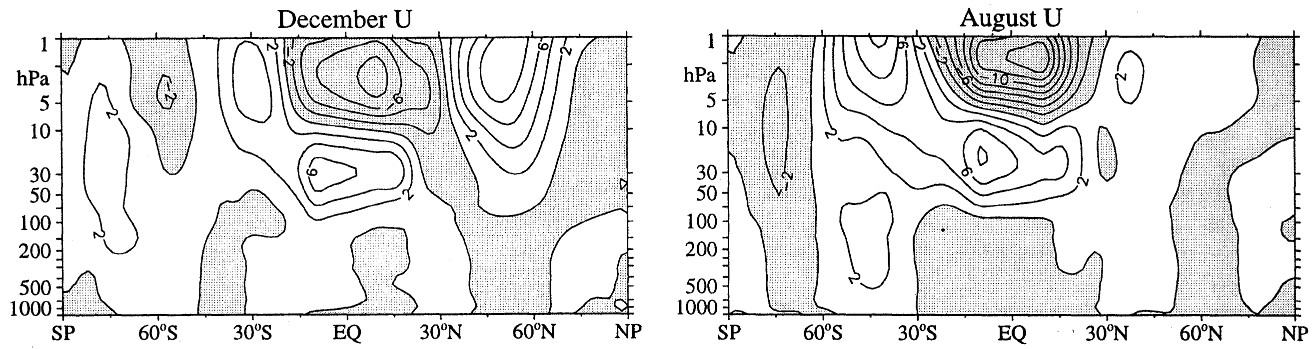

Figure 5. December (top) and August (bottom) latitude-height zonal-mean wind difference. The calculation is as in Figure 1, with the QBO phase calculated using u^* with ϕ=0° (top) and ϕ=50° (bottom).

1/1956–1/1998. We first regridded the data in the vertical, using cubic splines, onto 21 levels spaced equally in log-pressure. We found that, similar to *Wallace et al.* [1993], the first two EOFs accounted for over 94% of the variance of equatorial wind.

At each pressure level there is a value of ϕ that maximizes the correlation between u^* and the observed wind at that level. Listed below are the value of ϕ for each pressure level, together with the correlation between u^* and the observed winds at that level.

Level, hPa	ϕ	Correlation
10	136°	0.943
15	106°	0.986
20	76°	0.978
30	32°	0.978
40	3°	0.965
50	-15°	0.924
70	-54°	0.809

Selecting the optimum wind level to define the QBO has traditionally been used to maximize the magnitudes of composite differences of extratropical variables. The arbitrary phase adjustment, ϕ, makes this process explicit and allows for finer adjustments to the time series than simply picking one of the seven levels.

There is no a-priori reason to expect the optimum definition of the QBO phase to be exactly the same for the two hemispheres. For each hemisphere, the process of selecting a single value of ϕ is straightforward; we examined wind and temperature fields composited by time series of ψ, adding a range of arbitrary values of ϕ, and selected the single value of ϕ for each hemisphere that resulted in the largest extratropical signal. We found that ϕ=0° optimized the northern hemisphere composites, while ϕ=50° optimized the southern hemisphere composites. From Table 1, ϕ=0° corresponds very closely to the observed 40-hPa wind, while ϕ=50° coincides approximately with the 25-hPa level.

Results

The QBO's extratropical influence is perhaps best seen by forming the difference between east phase and west phase composites of zonal mean wind. Figure 1 illustrates the January latitude-height composite difference in zonal mean wind, using u^* with ϕ=0° to define the positive and negative phases of the QBO. To form the composite difference, the average of all Januaries with negative QBO phase was subtracted from the average of Januaries with positive phase. The northern signal is dominated by a modulation of the polar vortex that extends from the surface past 1 hPa. Differences are of the opposite sign south of ~45°N and blend into the upper branch of the QBO. The signal is strongest near 5 hPa in both the tropics and high northern latitudes. This dipole structure was first documented by *Nigam* [1990], and is the leading mode of variability of the northern extratropical stratosphere.

Figure 2 illustrates the 5-hPa seasonal development of the northern hemisphere zonal wind composite difference. The signal begins during autumn in midlatitudes, and reaches a high-latitude maximum during January. The late winter (February and March) composite difference is insignificant north of 40°. The abrupt diminution of the signal indicates that the QBO modulates the strength of the northern polar vortex during midwinter, but has little effect on the timing of the final warming [*Dunkerton and Baldwin*, 1992]. The northern hemisphere signal is consistent with the observation that major warmings do not occur before December, and occur most frequently in January. These observations are also consistent with the modeling study of *O'Sullivan and Dunkerton* [1994], described below.

The southern hemisphere polar vortex is much stronger, longer-lived, and more quiescent than its northern hemisphere counterpart. During winter, planetary waves do not significantly disrupt the southern vortex in the lower and middle stratosphere. As a consequence, the QBO does not appear to modulate the strength of the high-latitude vortex during midwinter. However, as shown in Figure 3, the QBO modulates the strength of winds in midlatitudes beginning in late autumn, as in the northern hemisphere. Unlike in the northern hemisphere, the wind modulation remains confined to midlatitudes throughout the winter and early spring. The striking difference between Figures 2 and 3 is that in the southern hemisphere, the largest influence of the QBO occurs during late spring (November), at the time of the final warming. The modulation of the southern vortex in October is of the same magnitude as that of the northern vortex in January. Since planetary-wave amplitudes are much smaller in the southern hemisphere, it is not surprising that the QBO's effect is seen only at the vortex periphery until the vortex is relatively small. Composites of temperature (not shown) indicate that throughout the winter the southern vortex is slightly colder in the west phase of the QBO.

The 5-hPa observations from Figures 2 and 3 may be compared to the (8-hPa) modeling results of *O'Sullivan and Dunkerton* [1994]. They used a mechanistic primitive equation model, with variable forcing at the lower boundary (10 km), to study the seasonal evolution of the QBO's influence on the northern winter circulation. With low-amplitude forcing the

QBO's phase had little effect until late winter – similar to what is observed in the southern hemisphere. For low forcing values the QBO's phase modulated the time of the final warming. With larger forcing, the QBO's effect was seen in midwinter (as sudden warmings when the QBO was in the east phase). The east phase warmings occurred early enough in the winter for the vortex to completely recover before the final warming. For the largest forcing the late winter vortex recovered to become stronger during late winter in the QBO east phase than the QBO west phase. This behavior is seen clearly in Figure 2.

The latitude-height structure of the zonal wind composite difference for November is illustrated in Figure 4. The magnitude of the vortex modulation is similar to that of the northern hemisphere (Figure 1), but the dipole structure in the northern hemisphere is not seen. Zonal-mean temperature (not shown) at high southern latitudes is modulated over the 150–5 hPa layer, being up to 3 K colder in the west phase of the QBO. The different definition of the QBO phase (u^* with ϕ=50° vs. 0° for the northern hemisphere) is reflected in the slightly higher maximum in equatorial wind (as expected, near 25 hPa), with the upper branch of the QBO located above 5 hPa. Unlike in the northern hemisphere, the high-latitude modulation of the vortex is not seen below the tropopause.

A comparison of Figures 2 and 3 shows that, at 5 hPa, the composite zonal wind difference in the northern hemisphere in December is comparable to that in the southern hemisphere during August. This analogy is further explored in Figure 5, for the latitude-height plane. In both hemispheres the maximum composite differences are found equatorward of 60° and above 5 hPa. The structure of the high-latitude vortex is unaffected. The most noticeable distinction is that in the northern hemisphere the connection to the lower branch of the QBO is not continuous, reflecting the formation of the dipole structure seen in January. The dipole is not seen in the southern hemisphere, where the modulation of the polar vortex connects to the lower branch of the QBO. This distinction may arise because the southern vortex extends ~10° farther equatorward during midwinter.

Conclusion

The QBO's wintertime influence on the southern polar vortex, as seen through monthly-average composites of zonal-mean wind, is similar in magnitude to its influence on the northern vortex. However, the timing and location of the QBO's effects are different in the two hemispheres. Throughout the period from late autumn to early spring, midlatitude zonal-mean winds in the southern hemisphere are modulated by the QBO, but the polar region is unaffected. This situation contrasts with the northern hemisphere, where the strongest influence is observed in January, reflecting the propensity for major stratospheric warmings to occur when the QBO is in its east phase. The largest southern hemisphere wind modulation occurs in November, at the time when the southern vortex undergoes its final warming, and is comparable to the QBO's northern hemisphere effect during January.

Acknowledgments. This research was supported by the National Science Foundation, grants ATM-9500613 and ATM-9708026, and by the National Aeronautics and Space Administration, contract NAS1-96071.

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(Received April 16, 1998; Revised June 16, 1998; accepted July 16, 1998.)