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Published Version

Anstey, J.A. and Shepherd, T. G. (2008) Response of the northern stratospheric polar vortex to the seasonal alignment of QBO phase transitions. Geophysical Research Letters, 35 (22). L22810. ISSN 0094-8276 doi: https://doi.org/10.1029/2008GL035721 Available at https://centaur.reading.ac.uk/31491/

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L22810, doi:10.1029/2008GL035721, 2008

Response of the northern stratospheric polar vortex to the seasonal alignment of QBO phase transitions

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Received 16 August 2008; revised 11 October 2008; accepted 28 October 2008; published 26 November 2008.

[1] This study considers the strength of the Northern Hemisphere Holton-Tan effect (HTE) in terms of the phase alignment of the quasi-biennial oscillation (QBO) with respect to the annual cycle. Using the ERA-40 Reanalysis, it is found that the early winter (Nov–Dec) and late winter (Feb–Mar) relation between QBO phase and the strength of the stratospheric polar vortex is optimized for subsets of the 44-year record that are chosen on the basis of the seasonality of QBO phase transitions at the 30 hPa level. The timing of phase transitions serves as a proxy for changes in the vertical structure of the QBO over the whole depth of the tropical stratosphere. The statistical significance of the Nov–Dec (Feb–Mar) HTE is greatest when 30 hPa QBO phase transitions occur 9–14 (4–9) months prior to the January of the NH winter in question. This suggests that there exists for both early and late winter a vertical structure of tropical stratospheric winds that is most effective at influencing the interannual variability of the polar vortex, and that an early (late) winter HTE is associated with an early (late) progression of QBO phase towards that structure. It is also shown that the seasonality of QBO phase transitions at 30 hPa varies on a decadal timescale, with transitions during the first half of the calendar year being relatively more common during the first half of the tropical radiosonde wind record. Combining these two results suggests that decadal changes in HTE strength could result from the changing seasonality of QBO phase transitions. **Citation:** Anstey, J. A., and T. G. Shepherd (2008), Response of the northern stratospheric polar vortex to the seasonal alignment of QBO phase transitions, *Geophys. Res. Lett.*, *35*, L22810, doi:10.1029/2008GL035721.

1. Introduction

[2] During winter in the Northern Hemisphere (NH) extratropical stratosphere there is large interannual variability in the strength of the polar vortex. *Holton and Tan* [1980] (hereinafter referred to as HT80) found this variability to be affected by the phase of the QBO, with equatorial westerlies (easterlies) at 50 hPa favouring a stronger (weaker) vortex. Later updates of HT80 [*Dunkerton and Baldwin*, 1991; *Naito and Hirota*, 1997; *Lu et al.*, 2008] upheld the existence of the Holton-Tan effect (HTE), but the statistical significance of the late winter signal compared to that of the early winter signal was reduced in the longer records, suggesting that the strength of the HTE may fluctuate on a decadal timescale.

[3] The origin of apparent decadal-scale variability in the HTE is unknown. One hypothesis is that the 11-year solar cycle modulates the HTE, causing it to fail [*Gray et al.*, 2001a] or possibly reverse [*Labitzke and van Loon*, 1988] during solar maxima. Another approach, taken recently by *Lu et al.* [2008] (hereinafter referred to as L08), was to isolate a subset of the record, 1977–1997, during which the late winter HTE appeared to reverse, or (given its low statistical significance) disappear. A late winter reversal is similar to the apparent solar cycle effect, but L08 noted that the 1977–1997 period samples roughly the same number of years of both solar cycle phases.

[4] HT80 suggested that the mechanism for QBO influence on the vortex is due to modulation by the QBO of the position of the low-latitude $\overline{u} = 0$ line, which acts as a barrier to the propagation of stationary planetary waves. The increased confinement of waves at high latitudes should weaken the vortex, but since the QBO winds in the lower and mid-stratosphere generally have opposite sign, the relation of the observed HTE to this mechanism is ambiguous. With vertical wavelengths spanning the depth of the stratosphere, planetary waves may be sensitive to the state of low-latitude winds over the whole stratospheric depth [*Gray et al.*, 2003].

[5] The relation between polar vortex variability and the location of the low-latitude $\overline{u} = 0$ line has been explored in numerous mechanistic modeling studies. Use of a deep ($\approx$15 km) layer of tropical easterlies, so that $\overline{u} = 0$ was located in the NH, was found to hasten the onset of warmings [*Holton and Austin*, 1991; *O'Sullivan and Young*, 1992; *O'Sullivan and Dunkerton*, 1994], but such a layer gives an unrealistic representation of the vertical structure of the QBO. Recent attempts to incorporate more realistic QBO vertical structure into similar studies have found that the HTE is sensitive to tropical winds over the whole stratospheric depth [*Gray et al.*, 2001b; *Gray*, 2003; *Gray et al.*, 2004].

[6] The vertical structure of tropical winds during NH winter is determined by the seasonal timing of QBO phase transitions. While transitions do not strictly synchronize with the annual cycle, neither are they wholly independent of it [*Dunkerton*, 1990]. They tend to cluster at certain times of the year more than others, for reasons that are not well understood. In a mechanistic modeling study, the strength of the HTE has been found to be sensitive to the phase alignment between the QBO and the annual cycle [*Hampson and Haynes*, 2006].

[7] In this study we examine the apparent decadal modulation of the HTE by partitioning the data into subsets based on the seasonality of QBO phase transitions. The timing of phase transitions at 30 hPa serves as a proxy for changes in the vertical structure of the QBO over its whole height range. Statistically significant HTE signals in early

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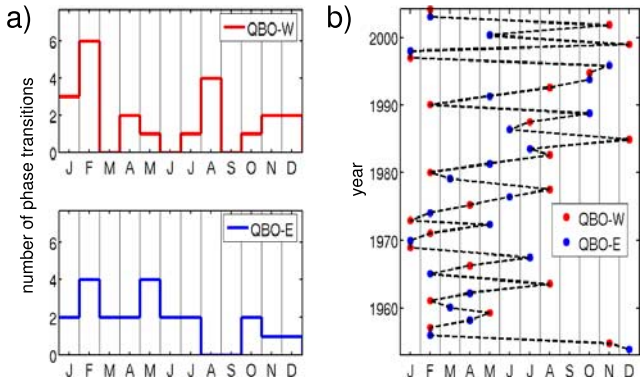

Figure 1. (a) Seasonality of QBO phase transitions at 30 hPa; (b) temporal variation of the seasonality shown in Figure 1a. The dashed lines connect consecutive QBO phases.

and late winter are found to occur for different subsets of the data. Based on this we hypothesize that the observed decadal variation of the HTE as described by L08 may result from decadal changes in the seasonal clustering of QBO phase transitions.

2. Methods

[8] We employ all 44 years (1958–2001) of monthly mean $\overline{u}$ from the ERA-40 Reanalysis [*Uppala et al.*, 2005], using public data from the ECMWF Web site (http://data.ecmwf.int/data/d/era40/) on 23 pressure levels from the surface to 1 hPa at 2.5° × 2.5° resolution.

[9] The QBO is defined by radiosonde winds measured at near-equatorial stations [*Naujokat*, 1986]. The data are deseasonalized by subtracting the 1953–2004 climatology, a five-month running mean is applied, and QBO phase at a given vertical level is defined as westerly (W) or easterly (E) by the sign of the wind. (Similar results are obtained if the 1958–2001 climatology is used, if ERA-40 $\overline{u}$ replaces radiosonde data, and if the running mean is not used.)

[10] To examine differences between states of the NH winter stratosphere that are composited by QBO phase, the data are partitioned into subsets defined by the timing of QBO phase transitions with respect to the annual cycle. A subset is defined by specifying a given range of lags, relative to NH winter, during which a QBO phase transition at a given vertical level may occur. If a W (E) phase initiates during that period, the NH winter is assigned to the W (E) category. For example: by choosing the period 4–9 months prior to any given January, and choosing the 30 hPa level, the sample is restricted to include only the winters for which a 30 hPa phase transition occurred sometime during the Apr–Sep period prior to those winters. The chosen period (Apr–Sep in the example) is denoted as the "phase bin", and the shorthand "months prior" denotes "months prior to January".

3. Results

[11] Figure 1 shows the seasonal timing of QBO phase transitions at 30 hPa for the 1953–2004 tropical radiosonde winds. The histogram (Figure 1a) shows that transitions tend to cluster at certain times of the year. (This plot updates Figure 4, for the 30 hPa level, of *Dunkerton* [1990].) Figure 1b shows the temporal variation of phase transition seasonality. The time series of phase transitions at other vertical levels (not shown) also show clustering.

[12] To attempt to isolate an influence of QBO vertical structure on the extratropical flow, we select two six-month phase bins, based on the 30 hPa phase transitions, for detailed consideration: Nov–Apr (9–14 months prior) and Apr–Sept (4–9 months prior). After eliminating years that lie outside the range of the ERA-40 data (1958–2001), the Nov–Apr bin contains 11 W and 9 E winters and the Apr–Sept bin contains 8 W and 10 E winters. To illustrate the effect of these bin choices on the vertical structure of tropical winds during NH winter, Figure 2 shows the W–E (W minus E) composite differences of ERA-40 $\overline{u}$ at 15N, for the two bins. The two bins differ by roughly a quarter-cycle in QBO phase.

[13] W–E composite differences of early (Nov–Dec) and late (Feb–Mar) winter ERA-40 winds for these phase bins are shown in Figure 3. For the Nov–Apr phase bin (Figures 3a and 3b), the early winter HTE is very strong while the late winter effect is weaker, and not statistically significant. Conversely, the Apr–Sept phase bin (Figures 3c and 3d) displays a statistically significant late winter effect, but no early winter polar effect. This suggests that the W–E tropical wind difference shown in Figure 2a (Figure 2b) may indicate a contrast between QBO states that effec-

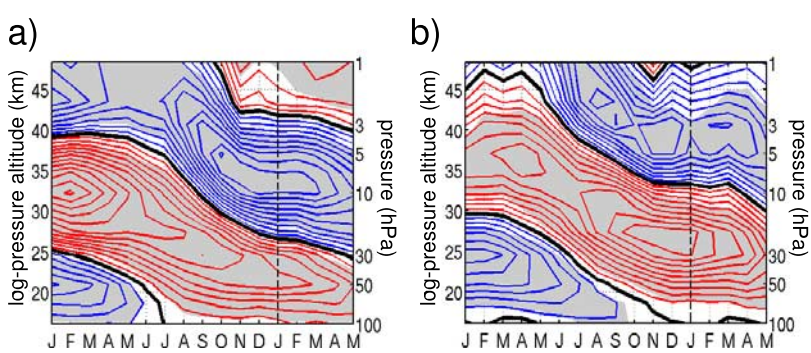

Figure 2. (a) W–E composite difference of ERA-40 15N zonal average zonal wind, $\overline{u}$, for the Nov–Apr (9–14 months prior) phase bin. The dashed line marks the January of the NH winter that is classified as W or E within the bin. (b) Same as Figure 2a but for the Apr–Sept (4–9 months prior) phase bin. Contour interval is 2 m/s, with red (blue) indicating positive (negative) values, the zero line in black, and 95% significant differences (by the *t*-test) are shaded.

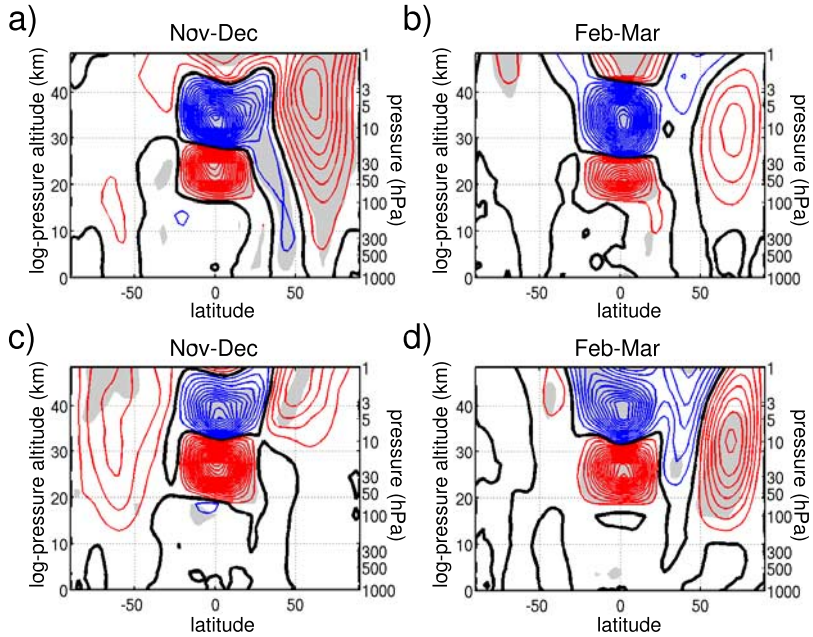

Figure 3. W–E composite differences of ERA-40 zonal average zonal wind, $\overline{u}$. Differences for the Nov–Apr (9–14 months prior) phase bin during (a) Nov–Dec and (b) Feb–Mar. Differences for the Apr–Sept (4–9 months prior) phase bin, also during (c) Nov–Dec and (d) Feb–Mar. Contour interval, colours and shading as in Figure 2.

tively excites an early (late) winter HTE. If correct, this in turn suggests - upon referring back to Figure 1b - that the HTE strength could fluctuate over the course of the observed record.

[14] We attempt to motivate, in Figure 4a, the emphasis that we have placed on the choice of the Nov–Apr and Apr–Sept phase bins. The ordinate shows the *t*-statistic at the 60N, 50 hPa gridpoint, using the form of *t* for which the two samples (W and E groups within a given phase bin) are assumed to have equal variance [*von Storch and Zwiers*, 1999]. The abscissa shows different six-month phase bins, varying their boundary months in one-month increments, and is labelled by the first month of a given six-month phase bin (hence the Nov–Apr and Apr–Sept bins of Figure 3 correspond to the earliest Nov and Apr, respectively, marked on the axis). Figure 4a shows that varying the boundaries of the six-month phase bins results in a relatively smooth variation of *t*, suggesting that the results are not sensitive to the exact choice of the phase bin.

[15] Some care is required when determining the statistical significance of the results shown in Figure 4a. To see this, we consider what would happen if we removed any linkage between the QBO and the polar vortex by replacing the 60N, 50 hPa time series with a white noise time series. Performing this exercise for $n = 5000$ white noise processes, it is found that the likelihood of obtaining large magnitudes of *t* for at least some of the phase bins is higher than the putative significance level of the *t*-value: if it were the case that all the phase bins contained independent data, then 1 in 20 of the *t*-values obtained from a white noise time series

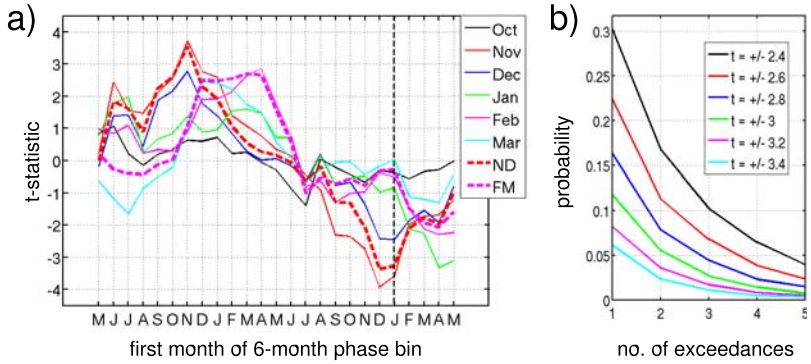

Figure 4. (a) *t*-statistic for zonal average zonal wind ($\overline{u}$) at 60N, 50 hPa as a function of 6-month phase bin. The Nov–Dec and Feb-Mar results are shown in bold dashed lines while the six months of NH winter are also shown separately. Vertical dashed line as in Figure 2. (b) Statistical test using $n = 5000$ random white noise values. This plot shows the probability of a given *t*-vs-bin curve, i.e., one of the curves shown in Figure 3a, achieving at least the number of exceedances of the given *t*-values under the null hypothesis that there exists no correlation between QBO phase and polar vortex variability (see text for details).

would exceed the 95% significance level. Of course the phase bins do not contain independent data because adjacent bins share some months. We therefore ask: what is the likelihood, under the null hypothesis (H_0) that the QBO and vortex are uncorrelated, of obtaining multiple exceedances of specified t thresholds? This likelihood is shown in Figure 4b. The Feb–Mar peak in Figure 4a contains five exceedances of $|t| = 2.4$; according to Figure 4b this has a 4% chance of occurring under H_0 (i.e. the Feb–Mar peak has a significance of 96%, by this test). The Feb peak, in contrast, contains two exceedances of $|t| = 2.6$, which has a 12% likelihood under H_0. The Nov–Dec peak has a 3% likelihood under H_0. If the 60N, 10 hPa gridpoint is used instead, the significance of the Nov signal increases while that of the late winter signal remains about the same. Replacing the white noise process with an AR1 process that mimics the intraseasonal autocorrelation of the polar vortex does not affect the significance of the results shown in Figure 4a.

4. Discussion

[16] While a correlation does not imply causality, confidence that our result reflects a causal QBO influence on the extratropics is provided by comparison with mechanistic modeling studies. *Hampson and Haynes* [2006] showed that the strength of the HTE was sensitive to the phase alignment of the QBO with respect to the annual cycle. Figure 4a indicates a systematic variation of this effect with changing phase bin, or equivalently with changing vertical structure of tropical winds during NH winter (as illustrated by Figure 2). *Gray et al.* [2004] varied the vertical position of a 10 km-deep tropical E perturbation in 5 km increments, and found the strongest HTE to occur when the perturbation occupied the 30–40 km layer: the onset of warmings, relative to the control run and to the other perturbed runs, was consistently delayed [see *Gray et al.*, 2004, Figure 4]. Figure 2a shows that a deep E phase in the 30–40 km layer is likely to occur in early winter (Oct–Dec) for the W group of the Nov–Apr phase bin, for which there is a stronger early winter vortex (Figure 3a).

[17] The variation of QBO phase transition clustering shown in Figure 1b suggests an explanation for L08's finding that a change in the HTE occurred during the period 1977–1997. Figure 1b indicates that during the 1977–1997 period, 8 out of 17 QBO phase transitions at 30 hPa occurred in the May–Aug period, a high number in comparison to the rest of the record (in which only 6 out of 27 transitions occurred during the May–Aug period). The remaining 9 transitions occurred during the Oct–Mar period, which Figure 4a shows is associated with a HTE in early, but not late, winter. Figure 4a also shows that a decrease in the late winter (Feb–Mar, or Feb) signal occurs when April (9 months prior) is eliminated from the phase bin, which suggests that the late winter HTE is absent for phase bins that are dominated by the May–Aug period. Hence the 1977–1997 period should display a statistically significant HTE signal in early winter, but not in late winter. This is consistent with Figure 6 of L08. Our analysis therefore suggests that the variation of the seasonal clustering of QBO phase transitions on a decadal timescale is responsible for there being a weak or nonexistent late winter HTE during the 1977–1997 period.

[18] If the effect we have diagnosed is real, it suggests that decadal-scale variations in the HTE may arise due to internal atmospheric variability. However, the exact mechanisms that cause the decadal clustering of QBO phase transitions (Figure 1b) are not known, and it is possible that external forcings influence the clustering through some unknown mechanism. Addressing this issue will require either much longer data sets or modeling studies.

[19] **Acknowledgments.** This work was supported by the Natural Sciences and Engineering Research Council of Canada. The authors would like to thank John Scinocca for helpful discussions, and Mark Baldwin and an anonymous reviewer for helpful comments.

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