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Effects of the El Niño–Southern Oscillation and the Quasi-Biennial Oscillation on polar temperatures in the stratosphere

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[1] Reanalysis data are used to study the effects of the Quasi-Biennial Oscillation (QBO) and the El Niño–Southern Oscillation (ENSO) on the stratosphere. During the boreal winter in the Arctic, Warm ENSO (WENSO) months are found to be significantly warmer and Cold ENSO (CENSO) months significantly colder than climatology. The QBO is also found to have a large effect on the Arctic stratosphere during the late fall/early winter; Westerly QBO (WQBO) poles are colder, and Easterly QBO (EQBO) poles are warmer. In the first half of the 50 years of interest, WENSO and EQBO have had a tendency to be correlated in time, and thus their signals are difficult to disentangle. In order to isolate each effect from the other, composites are taken of QBO months under near-neutral ENSO conditions, which show a clear effect in late fall/early winter. Because of the bimodality of QBO, producing a meaningful composite of ENSO months under near-neutral QBO is difficult, as the number of available months is quite small. To distinguish ENSO from QBO and to further study the QBO, we compare composites of months with four different combinations of QBO and ENSO anomalies, which confirms that ENSO does have a significant effect on the polar vortex. These groupings are also studied after removing the 2 years following one of the three major volcanic eruptions during the 50 years of data and during the post-1979 satellite era only as well. These composites show distinct ENSO and QBO effects of comparable magnitude.

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1. Introduction

[2] Much has been written about the extratropical effects of the QBO. *Holton and Tan* [1980] first noted that the zonal mean geopotential height at high latitudes is significantly lower during the westerly phase of the QBO at 50 mbar than during the easterly phase. They hypothesized that the QBO modulates the location of the critical wind line, thus affecting the propagation of planetary waves from the troposphere into the stratosphere. Since then, many modeling-based studies [e.g., *Hampson and Haynes*, 2006; *Pascoe et al.*, 2006; *Naito and Yoden*, 2006; *Kinnersley and Tung*, 1999] and data based studies [e.g., *Ruzmaikin et al.*, 2005; *Baldwin and Dunkerton*, 1998] have analyzed the effects the QBO has on the polar vortex, and at the level of detail discussed in this paper, reached similar conclusions. *Baldwin and Dunkerton* [1998] found that the QBO at 25 mbar has the greatest influence on the Antarctic, and that the QBO at 40 mbar influences the Arctic the most. *Hampson and Haynes* [2006] found that the QBO at ∼48 mbar gives maximum Northern Hemisphere extratropical response. *Baldwin et al.* [2001] summarized much of the early work done on the subject.

[3] *van Loon et al.* [1982] and *van Loon and Labitzke* [1987] attempted to discern the effect that ENSO has on the Northern Hemisphere polar stratosphere, and to differentiate between the effects of the QBO and ENSO, using data. However, similar attempts by *Hamilton* [1993] showed that the ENSO signal was not separable from the QBO signal in a statistically significant manner. More recently, *Sassi et al.* [2004] forced a General Circulation Model (GCM) with observed sea surface temperatures (SSTs) from 1950–2000 and found that while WENSO leads to a significantly warmer polar stratosphere, CENSO is statistically indistinguishable from the mean. The effect was more pronounced in late winter to early spring. *Manzini et al.* [2006] and *Garcia-Herrera et al.* [2006] compared model results forced with observed SSTs and ERA-40 data from 1980–1999, and they found that while WENSO winters were significantly warmer than neutral ENSO months in the Arctic stratosphere, the CENSO cooling was weaker; *Manzini et al.* [2006] found that the signal propagated downward over the course of the winter, such that the upper stratospheric signal was most pronounced in early winter and the lower stratospheric effect strongest in late winter. *Taguchi and Hartmann* [2006] forced a GCM for 9125 days with perpetual January conditions under both WENSO and

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Table 1a. WQBO Versus EQBO in the Arctic in OND Under Neutral ENSO[a]

	|ENSO| < 0.3	|ENSO| < 0.5
|QBO| > 0.4	−**2.3**,16,−3.1,13, 7	−**1.8**,32,−2.5,17,20
|QBO| > 0.7	−**2.5**,14,−3.7,11, 6	−**1.9**,29,−2.9,15,19
|QBO| > 1.0	−1.5, 7,−2.0, 7, 3	−1.7,18,−3.1, 8,14

[a]The first number is the t score, the second is the number of degrees of freedom, the third is the difference between the means (WQBO-EQBO) in °C, the fourth is the number of WQBO months that fit the requirements, and the last is the number of EQBO months that fit the requirements. Bolded t-scores are significant at 95% in this and all future tables. All tables based on ERA-40 QBO index and Nino3 ENSO index.

CENSO SST conditions in the Pacific, and found more Sudden Stratospheric Warmings and a more disturbed vortex under WENSO than CENSO conditions. None of these models include a realistic QBO, thus demonstrating that in models at least, ENSO affects the polar vortex even in the absence of the QBO.

[4] The papers that have discussed the observational evidence generally noted that the influence of the QBO obscures much of the ENSO signal that may exist, noting that WENSO tends to be phase aligned with EQBO at 50 mbar during the winter season. This seemed to dissuade many of them from commenting on the significance of the noted ENSO change, and even those who proceeded to evaluate significance found none. The only exception is the study by *Camp and Tung* [2007b], where Linear Discriminant Analysis is used to show that the ENSO signal is of comparable magnitude to that of the QBO. Thus models have been the main instrument used thus far to differentiate the effects of the QBO(ENSO) from that of ENSO(QBO) in a statistically significant fashion.

[5] Volcanoes might also affect the polar stratosphere. *Free and Angell* [2002], *Rind et al.* [1992], and others have found that the tropical lower stratosphere was affected by the Pinatubo, El Chicòn, and Agung eruptions, though whether the polar midstratosphere was also affected is less clear. To eliminate as well as isolate any possible effect volcanoes may have, all analysis that yielded significant results here were performed both with and without the two years after each of the volcanic eruptions.

[6] The aim of this paper is to extract the independent effects of ENSO and QBO through a simple compositing analysis. To do so, we look at reanalysis data over the last 50 years and also for the more recent satellite era, and analyze when the temperature in the Arctic polar stratosphere is statistically significantly different from climatology. This paper also touches briefly on whether ENSO or QBO have an effect on the Antarctic polar vortex.

2. Data

[7] The monthly means produced by the European Center for Medium-Range Weather Forecasts (ECMWF) are used. The ERA-40 data set is used for the first 45 years, and the analysis is extended to the present by using operational ECMWF TOGA analysis. ERA-40 is a second generation reanalysis and is more accurate than earlier, first generation, reanalyses [*Uppala et al.*, 2005]. All statistical tests that result in significant results when performed on the entire 50 years of data are repeated for the shorter satellite era.

[8] At the time this paper is being written, ECMWF TOGA data is accessible up to and including January 2007. The ENSO and QBO indices of February 2007 were such that it would not be included in any of the composites mentioned below. The months of March through August are not used in this analysis. Thus all relevant data from the period September 1957 to August 2007 are included in this analysis, yielding 50 years of data.

[9] The climatological monthly means were first subtracted from the ECMWF 1200 UTC data. Then, the zonally averaged, area weighted temperature anomaly poleward of 70° at 10 mbar in both hemispheres was computed for each month in the 50 years of data. This averaged temperature is then used as a proxy for the strength of the polar vortex and is the quantity examined in the rest of this paper. Finally, only those months with the QBO and ENSO indices in the desired states, and which fall in the desired season, are composited together.

[10] For the Northern Hemisphere's vortex, when studying the ENSO effects, the extended winter of NDJF (November/December/January/February) is examined, and for studying the QBO effects, the late fall/early winter period of ONDJ (October/November/December/January) is examined. *Labitzke et al.* [2006], *Camp and Tung* [2007a], *Ruzmaikin and Feynman* [2002], and others have found a significant impact of the solar cycle on the polar vortex, predominantly in February and March. The upper stratospheric winds may also influence the late winter polar vortex strength [*Gray*, 2003]. To avoid these issues, our QBO composites exclude the late winter months entirely. For the Southern Hemisphere's vortex, the spring warming period of OND (October/November/December) is studied.

[11] The ENSO index used is the Nino3 index from the CPC/NCEP (http://www.cpc.noaa.gov/data/indices/sstoi.indices). We also reproduced some of the results below using the Nino3.4 index, the Nino4 index, the Nino1.2 index, and JISAO's Cold Tongue Index, which averages over a larger area than the Nino 3.4 index (http://jisao.washington.edu/data/cti/). The differences in the charts and graphs in sections 5 and 6 between the various indices were minor, with the results from Nino1.2 the most different from the other four.

[12] The QBO index used is the zonal mean, 10°S–10°N area averaged zonal wind from the ECMWF data at 50 mbar and 20 mbar. *Pascoe et al.* [2005] found that the ERA-40 accurately describes the tropical stratosphere up to 5 mbar, and *Baldwin and Gray* [2005] found the ERA-40 to accurately describe the QBO at levels even above 10 mbar. The Free University of Berlin (FUB) QBO index at 50 mbar is also used at various points to confirm results obtained with the ERA-40 index. The correlation between the two is 0.96.

Table 1b. Same as Table 1a but Excluding 2 Years After Volcanic Eruptions[a]

	|ENSO| < 0.3	|ENSO| < 0.5
|QBO| > 0.4	−**2.0**,14,−3.3,12, 5	−1.7,29,−2.5,16,18
|QBO| > 0.7	−**2.2**,12,−4.2,11, 4	−**1.8**,27,−2.8,15,17
|QBO| > 1.0	−0.8, 6,−1.3, 7, 2	−1.6,17,−3.0, 8,13

[a]As in Table 1a footnotes.

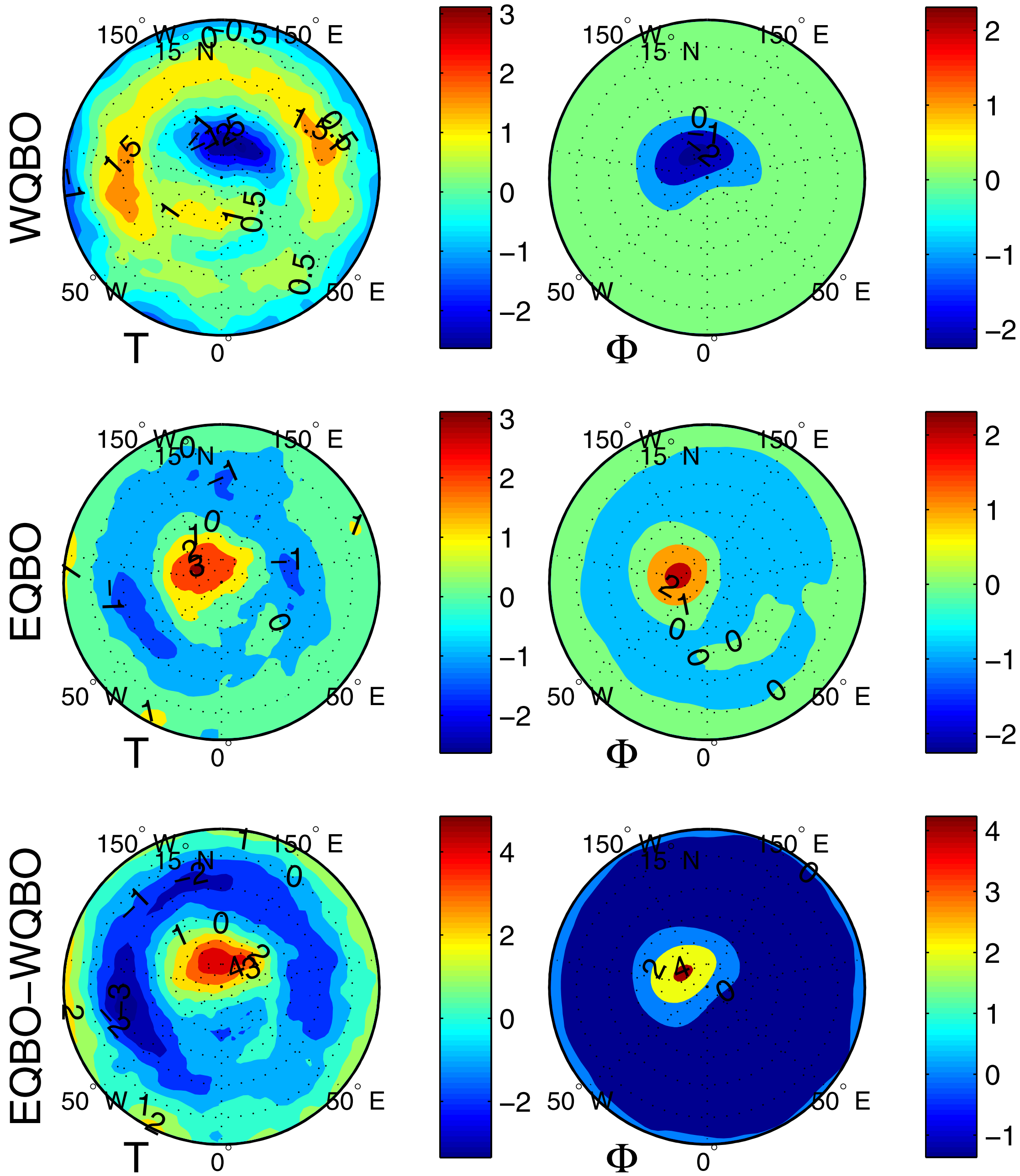

Figure 1. Composites of the temperature and geopotential anomalies of October, November, and December over the NH at 10 hPa under near-neutral ENSO (limit combination: $|\mathrm{ENSO}| < 0.4$, $|\mathrm{QBO}| > 0.7$). In this and all future plots, polar-stereographic projections are used, temperatures are in units of Celsius, geopotentials are in units of km m s^{-2}, and all 50 years are included. Except for Figure 7, the lowest latitude shown is 5°N, and the thin-dashed latitude lines are at 15°N, 30°N, 45°N, 60°N, and 75°N.

[13] Following *Hampson and Haynes* [2006], the QBO index at 50 mbar is applied to the Arctic, and following *Naito* [2002] and *Baldwin and Dunkerton* [1998], the QBO at 20 mbar is applied to the Antarctic. We tried applying the 50 mbar QBO to the Antarctic and observed no signal whatsoever, confirming *Naito* [2002].

[14] All indices were normalized by their standard deviation over all 593 months from September 1957 to January 2007 before use. A month is considered to be a QBO or ENSO month if the ENSO/QBO index exceeds a certain fraction of a standard deviation from its mean value. This lower bound is ranged from as low as 0.2 standard deviations to as high as 1.2 standard deviations in the various comparisons that appear here, in order to test the sensitivity of the results to excluding or including moderate ENSO/QBO months. In the rest of this paper, the units of indices are standard deviations, but these units are left out for brevity.

[15] Student t-tests can be used when the population the sample is drawn from is normally distributed. Visual inspection of the histograms of the temperature anomalies at 10 mbar from DJF, NDJF, and ONDJF in the Arctic

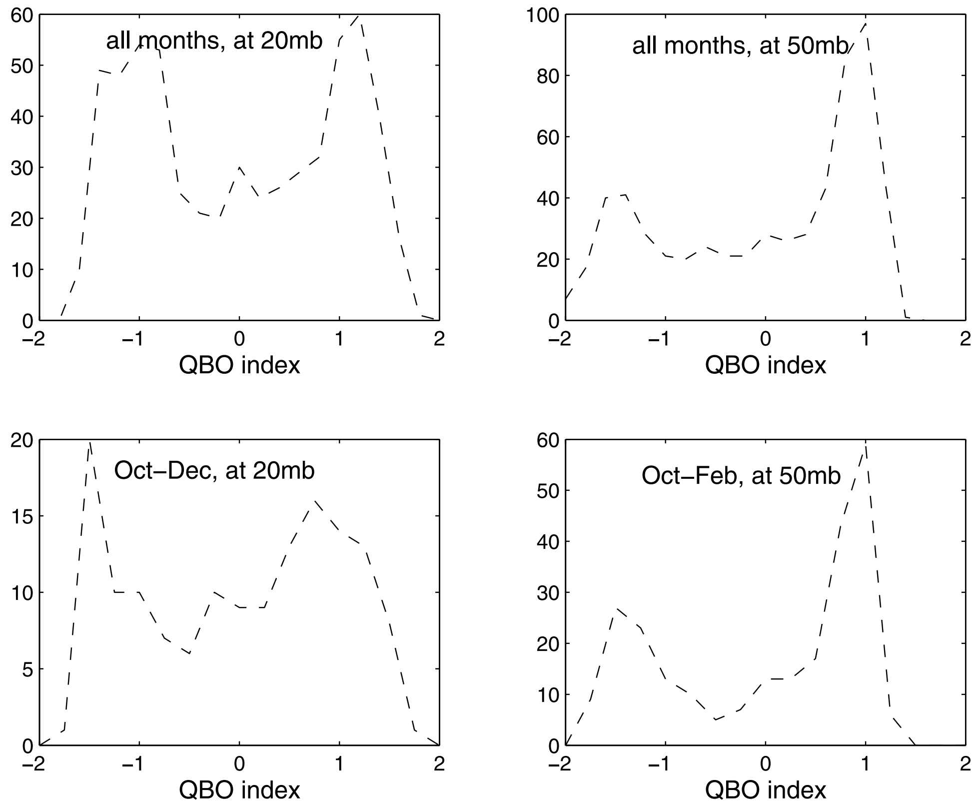

Figure 2. Histogram of ERA-40 QBO indices at 50 hPa and 20 hPa over the 593 months data was available. Histograms are shown for both the entire year and during the relevant season. Units are standard deviations.

confirm that they look Gaussian. Three quantitative tests were also used to test the normality of the distribution. The first two are Monte Carlo–like tests of the kurtosis and skewness expected when 150 (corresponding to 3 50 DJF months), 200 (corresponding to 4 50 NDJF months), and 250 (corresponding to 550 ONDJF months) numbers are drawn at random from a pure Gaussian distribution. The third is a χ^2 goodness-of-fit test comparing the histograms of DJF, NDJF, and ONDJF to a Gaussian. Details of these tests are not shown. These tests demonstrate that the temperature anomalies from 70°N poleward are normally distributed, thus justifying the use of Student t-tests. In the Antarctic, however, two of the three tests indicate that temperature anomalies in OND at 10 mbar are not normally distributed.

[16] The 10 mbar level is chosen as a balance between two constraints. The first constraint is due to an underlying assumption of this paper that the modulation of the polar vortex is simultaneous with ENSO or QBO conditions. The presumed mechanism by which anomalous polar vortices are brought about under QBO and ENSO is through anomalous heat flux convergence in the polar stratosphere (the veracity of this assumption is not examined here). *Newman et al.* [2001] found that the temperature of the polar vortex at 50 mbar is dependent on the heat flux in the previous month and a half. However, when the temperature of the polar vortex at a higher level is chosen, where radiative relaxation occurs more quickly, shorter lead times can be taken (*Newman et al.* [2001] found a 15 day damping timescale between 10 mbar temperature and heat flux). Thus it is desirable to choose as high a level as possible. Furthermore, *Baldwin and Dunkerton* [1999] and *Limpasuvan et al.* [2004, 2005] showed that anomalies in the polar vortex propagate downward with a timescale for descent from the upper stratosphere to the surface of 3 weeks. The downward propagation occurs because of the nature of the wave-mean flow interaction. The wave breaking occurs first at higher altitudes. As the winds weaken, the wave breaking occurs at lower altitudes. Thus the higher a level chosen, the less lag one would expect between the observation of anomalous ENSO and QBO conditions and the observed weaker/stronger vortex. The second constraint is that ERA-40 has been found to have inaccuracies above the 10 mbar level, and in particular above the 5 mbar level [*Randel et al.*, 2004]. Thus 10 mbar is the optimal level for our purposes.

[17] We tested the assumption that ENSO/QBO affect the polar temperatures during the same month that they are observed. We looked for polar temperature responses to ENSO and QBO in simultaneous months and also in months lagged one month behind the ENSO/QBO indices. As expected, simultaneous composites showed the largest response.

[18] In our analysis, we combine consecutive months where the same response to QBO/ENSO is expected (for example, NDJF are combined in the Arctic when a response to ENSO is expected). This raises the number of degrees of freedom in the analysis, thus allowing smaller differences to be significant. However, if one concatenates consecutive months together, the number of degrees of freedom may be

Table 2a. WENSO in the Arctic in NDJF Under Neutral QBO[a]

	|ENSO| > 0.4	|ENSO| > 0.7	|ENSO| > 0.9
|QBO| < 0.3	1.5,12,3.0,13	**3.3**, 8,5.3, 9	**2.6**, 6,5.1, 7
|QBO| < 0.5	**2.1**,14,4.3,15	**4.0**,10,6.6,11	**2.9**, 7,6.5, 8

[a]Same as Table 1, except the third number is the difference in temperature between the WENSO months and climatology in °C, and the fourth is the number of WENSO months that fit the requirements.

less than the number of months if the autocorrelation from month to month is significant. (One reason to expect persistence in polar temperature anomalies not due to the forcing from ENSO/QBO might be due to the slow relaxation to climatology following a Sudden Stratospheric Warming; however, studying the 10 mbar level, and not lower stratospheric levels, reduces this effect. An equal and perhaps even more important reason for the persistence is the dynamical feedback. When the vortex is strong it resists wave driving by ducting wave energy away. When it is weak, waves more easily penetrate the vortex and break, thereby keeping the vortex weakened.)

[19] The degrees of freedom are thus calculated using the formula of *Bretherton et al.* [1999] $N = N^* \frac{1-r(\Delta\tau)^2}{1+r(\Delta\tau)^2}$, where N^* is the number of months, and $r(\Delta\tau)$ is the autocorrelation at lag $\Delta\tau$, where $\Delta\tau$ is generally chosen to be one month. The best number to use is the month-to-month autocorrelation for the 3 or 4 months of October through February that are actually being used in a given analysis.

[20] For the Arctic polar vortex, the correct degrees of freedom for an OND composite is 86% of the number of months of data; for a NDJF composite, it is 98%, and for an ONDJ composite, it is 92%. However, we do not use consecutive months because only months in the appropriate phase of ENSO and QBO are included in a composite. Thus we really want the autocorrelation for 10–50 months sprinkled pseudorandomly through the data set, which would allow more degrees of freedom than the above numbers.

[21] In practice, for the Arctic analysis below, we reduce the degrees of freedom by the lag 1 month autocorrelation over the entire record. This yields an effective number of degrees of freedom of 91.7% of the number of months that exist. Because we are being conservative, results that barely miss significance may in fact be significant.

[22] For the Antarctic, the correction for an OND composite due to the lag-1 month autocorrelation is 87%. In addition, the Antarctic has large autocorrelation at lag 12 months; for example, the correction needed if a composite of only November is taken is 68%. Thus 68%, and not 87%, is used as the correction for Antarctic composites in the rest of this paper. This high autocorrelation was not unique to the presatellite era; the autocorrelation in the temperature anomalies stayed large in the satellite (post 1979) era (in contrast, the geopotential anomalies' autocorrelation dropped noticeably in the postsatellite era).

Table 2b. Same as Table 2a but Excluding Volcanic Months[a]

	|ENSO| > 0.4	|ENSO| > 0.7	|ENSO| > 0.9
|QBO| < 0.3	0.6, 8,1.6, 9	**3.0**, 5,4.6, 5	1.8, 3,3.8, 3
|QBO| < 0.5	1.4,10,3.7,11	**3.4**, 6,7.0, 7	1.9, 4,6.9, 4

[a]As in Table 2a footnotes.

Table 2c. Same as Table 2a but Excluding Presatellite Era[a]

	|ENSO| > 0.4	|ENSO| > 0.7	|ENSO| > 0.9
|QBO| < 0.3	**2.8**, 7,5.0, 8	**2.2**, 6,5.4, 6	1.7, 5,4.8, 5
|QBO| < 0.5	**3.6**, 9,6.6,10	**3.2**, 7,7.3, 8	**2.2**, 6,6.7, 6

[a]As in Table 2a footnotes.

This curiosity was not investigated further and seems to be an artifact of ERA-40.

[23] Finally, we also tried assigning 1 DOF (degree of freedom) when 2 or 3 consecutive months fit in the same phase of ENSO/QBO, and 2 DOF when 4 consecutive months fit in the same phase of ENSO/QBO, with the average temperature over those months used as the temperature of this DOF. We then examined whether the composites in sections 5 and 6 that give significant results would still be significant. In general, the signal did not change, the number of degrees of freedom dropped sharply, but the variance within each sample also dropped. Significance did drop slightly for some results, but all results shown as significant in this paper were still significant, except for the QBO under neutral ENSO case in Table 1 where significance was largely lost.

[24] Section 3 addresses the influence of ENSO without removing QBO. For brevity, a similar section detailing the influence of the QBO without removing ENSO is not included as our results are consistent with earlier work, with the dominant effects in late fall and early winter [*Hampson and Haynes*, 2006]. Section 4 studies the degree of correlation between ENSO and QBO. Sections 5 and 6 attempt to isolate the respective influences of ENSO and QBO. Figures and tables are included when significant results have been attained. For significant results, the geographic areas that warm/cool at 10 mbar are compared to those areas which warm/cool at 30 mbar (the above discussion regarding the desirability of choosing a high level is still somewhat applicable at 30 mbar), to see if the signal is entirely barotropic.

3. Analysis of ENSO Without Removing QBO

[25] Months are composited as ENSO months if the absolute value of their Nino3 index is greater than a certain limit. This limit is varied to examine the sensitivity of the results to excluding or including moderate ENSO months. No significant signals are observed in the Antarctic.

[26] For the Arctic, a NDJF composite is used. WENSO prevailed in 48 out of the 200 NDJF months during these 50 years, when the limit is taken at 0.75. The mean temperature at 10 mbar, poleward of 70°, increased 2.45°C from climatology, which is significant at the 98% level. 55 NDJF months had a Nino3 index below −0.75, and their mean stratospheric temperature anomaly is −2.29°C, which is significant at the 97.5% level. The difference between the means of CENSO and WENSO is significant above the 99% level. For WENSO, significant results are obtained for all values of limit above 0.55, with a peak in significance for limit = 0.80. For CENSO, significant results are obtained for all values of limit above 0.45, with a peak in significance at limit = 0.85 and again at limit = 1.4. If satellite era data only is used, WENSO's signal grows sharply and actually becomes even more significant, but CENSO's signal shrinks slightly and the

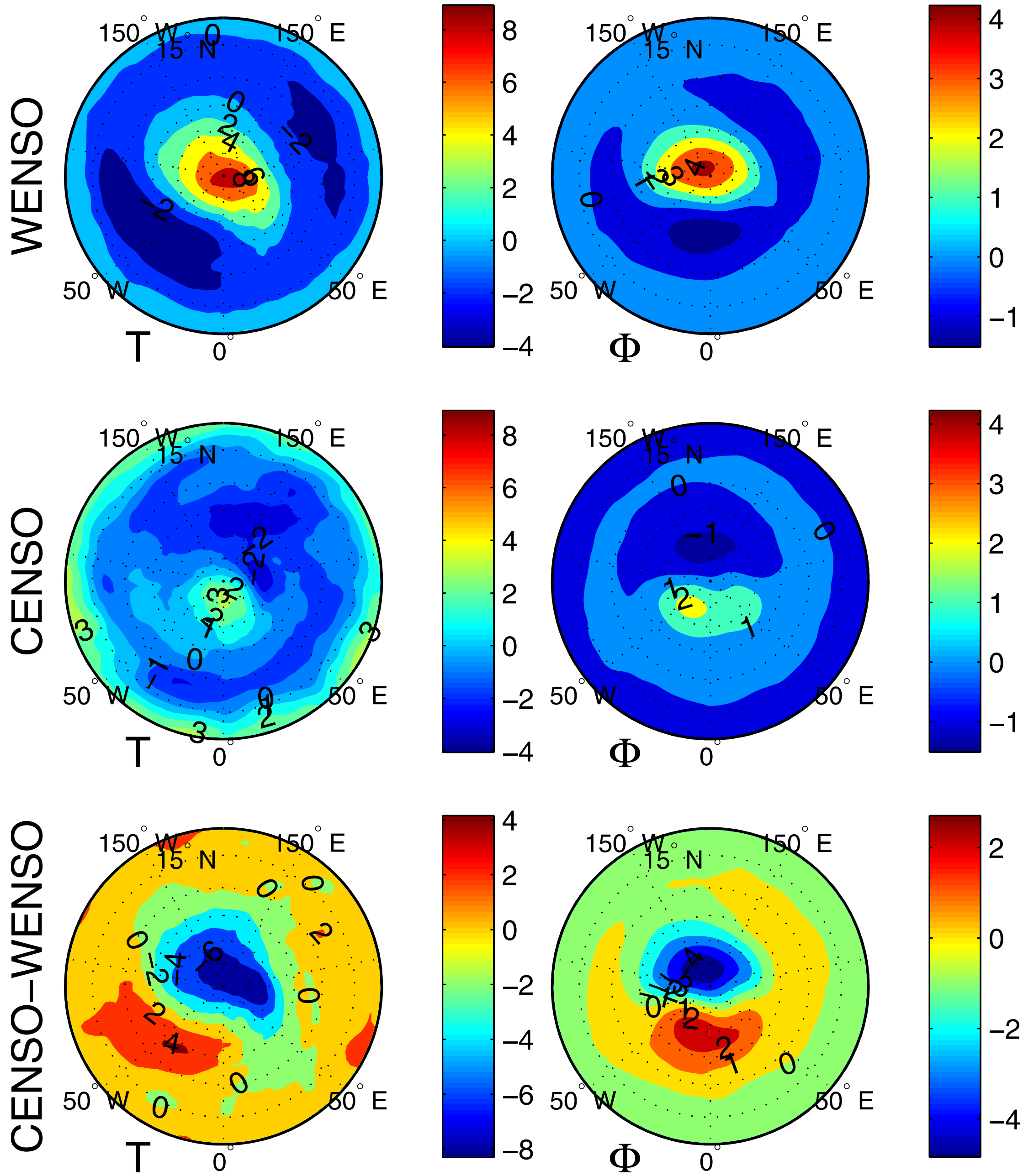

Figure 3. Composites of the temperature and geopotential anomalies of NDJF over the NH at 10 hPa under near-neutral QBO (limit combination: |ENSO| > 0.7, |QBO| < 0.5).

loss of 22 years of data results in significance not being attained. Charts and graphs demonstrating these results are not shown for brevity.

4. Correlation of QBO and ENSO

[27] *Xu* [1992] showed that the QBO and ENSO were not related in the time period from 1951 to 1986, and *Kane* [2004] reached the same conclusion from more recent data, but many others have either assumed or demonstrated there is a connection between the two, particularly in the boreal winter season. So before trying to separate the effects of QBO and ENSO, we first examine the correlation of the two indices from September 1957 to January 2007. The indices

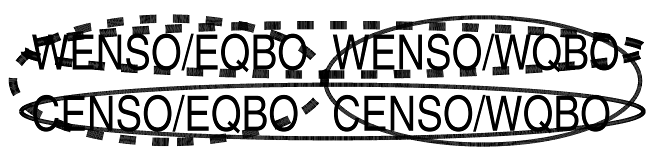

Figure 4. Categories examined in section 6. For the Arctic, the four circled comparisons are made. For the Antarctic, these four plus one diagonal comparison are made. The comparisons indicated by the solid ovals give significant results for the Arctic, while the comparisons indicated by the dashed ovals do not.

Table 3a. WENSO/WQBO Versus CENSO/WQBO in the Arctic in NDJF[a]

	|ENSO| > 0.4	|ENSO| > 0.8	|ENSO| > 1.2
QBO > 0.4	**2.1**,66,4.0,32,42	**3.1**,50,6.5,26,31	**3.3**,30,9.2,18,17
QBO > 0.6	**2.3**,59,4.5,30,37	**3.4**,44,7.6,24,26	**3.7**,27,10.1,17,15
QBO > 0.8	1.7,46,3.3,24,28	**2.1**,35,5.1,19,21	**2.5**,22,7.7,13,13

[a]Same as Table 1, except the third number is the difference in means (WENSO-CENSO) in units of °C, the fourth number is the number of WENSO months that fit the requirements, and the last number is the number of CENSO months that fit the requirements.

are defined such that when EQBO occurs in tandem with WENSO (the commonly assumed direction), the correlation is negative. The QBO at 50 mbar is used.

[28] The correlation coefficient of our QBO and ENSO indices for all 593 months is −0.02; the sample correlation is essentially zero. The correlation between the two indices starting in 1957 up until August 1982 (the 300th month) is −0.25, and the correlation from 1957 until December 1990 (the 400th month) is −0.16. The correlation from the 300th to the 593th month is 0.16, and the correlation from the 400th to the 593rd month is 0.26. Thus the correlation is not stationary in time. However, the most relevant months for this study are those in the boreal winter; thus we also evaluate whether the frequently assumed correlation is nonstationary even in the boreal winter.

[29] The correlation coefficient of the QBO and ENSO for NDJF for the entire 50-year period is 0.035. If the start and end date used in this correlation are chosen so as to maximize the absolute value of the correlation, while still choosing a period of at least 20 years, deft choice of years can give a correlation coefficient of −0.35 during the first half of the period and approaching 0.25 in the second half of the period. Similar results were obtained for OND: during the first half of the period, EQBO and WENSO could be interpreted as statistically significantly correlated (negative correlation coefficient), while in the second half of the period, EQBO and CENSO seem correlated (positive correlation coefficient).

[30] Thus the correlation is not stationary, and any proposed physical/dynamical explanation for the connection between QBO and ENSO should explain this nonstationary behavior. Previous work that found a correlation was performed in the early 1990s before the most recent data existed, and thus drew conclusions prematurely. Our conclusion is that the high correlation in the early part of the period most likely occurred by chance.

5. Analysis of QBO/ENSO for Near-Neutral ENSO/QBO Conditions

5.1. Effects of QBO Under Near-Neutral ENSO

[31] Months are composited as QBO months if the absolute value of their QBO index is greater than a certain limit. This limit is varied to examine the sensitivity of the results to excluding or including moderate QBO months. Months are only included if their Nino3 Index is below a second limit. This second limit is also varied in order to ascertain sensitivity. The limit associated with QBO is the minimum QBO still qualifiable as nonneutral, and the limit associated with ENSO is the maximum ENSO still considered neutral. The difference of means test between WQBO and EQBO is performed to see if a statistically robust difference between the two emerges.

Table 3b. Same as Table 3a but Excluding 2 Years After Volcanic Eruptions[a]

	|ENSO| > 0.4	|ENSO| > 0.8	|ENSO| > 1.2
QBO > 0.4	**2.0**,56,4.3,25,38	**3.0**,41,7.2,20,27	**2.8**,26,8.6,14,16
QBO > 0.6	**2.2**,51,4.8,24,34	**3.3**,37,8.2,19,23	**3.3**,24,9.7,14,14
QBO > 0.8	1.5,37,3.3,18,25	**1.9**,27,5.2,14,18	**2.0**,18,6.6,10,12

[a]As in Table 3a footnotes.

Table 3c. Same as Table 3b but Only Using Satellite Era Data[a]

	|ENSO| > 0.4	|ENSO| > 0.8	|ENSO| > 1.2
QBO > 0.4	1.3,31,3.7,18,18	**2.7**,21,8.1,13,12	**3.3**,13,10.9,10, 6
QBO > 0.6	1.3,30,3.7,17,18	**2.7**,20,8.4,12,12	**3.3**,13,10.9,10, 6
QBO > 0.8	1.2,20,3.5,11,13	1.5,14,6.1, 7,10	**2.4**, 9,10.3, 6, 6

[a]As in Table 3a footnotes.

[32] For the Antarctic, for a 20 mbar QBO index, a noticeable effect is present, but it is not significant at 95% for any combination of limits or months from October through December.

[33] For the Arctic, the late fall/early winter months of October, November, and December are combined and the analysis is done on this concatenation. Table 1a contains the t-statistics and degrees of freedom for a wide range of limits. The first two rows of Table 1a are all significant. Table 1b contains the same chart but excludes the first 24 months after a volcanic eruption. The reduced significance is minor, and is due to the reduced number of degrees of freedom taken, as the underlying signal actually strengthens. Finally, it should be noted that most of the effect is located within the EQBO months. The EQBO months are, for a wide range of limits, significantly different from climatology (not shown), but the WQBO months are not. This discrepancy in the strength of the response is also evident in Figure 1, where the temperature change is larger and centered more over the pole in EQBO than in WQBO. The decline in the signal from |QBO| > 0.7 to |QBO| > 1.0 is possibly consistent with *Naito et al.* [2003], where too strong a WQBO forcing leads to increased Sudden Stratospheric Warmings, and thus to warmer temperatures, than a slightly weaker WQBO forcing. *Naito et al.* [2003] found that this effect was only relevant for unrealistic WQBO amplitudes, however.

[34] Including January in the composite leads to uniformly lower significance, and in some cases takes results strongly significant at 95% and makes them not significant (not shown). Thus this composite is restricted to late fall.

[35] Finally, this analysis is repeated using only satellite era data. The signal drops substantially and statistical significance at 95% is not achieved. The pocket of cold air centered just off the pole in WQBO stays roughly of the same strength and size, but the warming associated with EQBO is much weaker than when the entire period is used.

[36] Figure 1 shows the geopotential and temperature anomalies for the composites of EQBO and WQBO for the case of |QBO| > 0.7 and |ENSO| < 0.4. All 50 years are used. The plots for all combinations of limits which yield significant results look similar, with what appears to be a weaker Aleutian High in WQBO, and a slightly more symmetric response in EQBO. The plots look qualitatively similar if produced at the 30 mbar level, though the

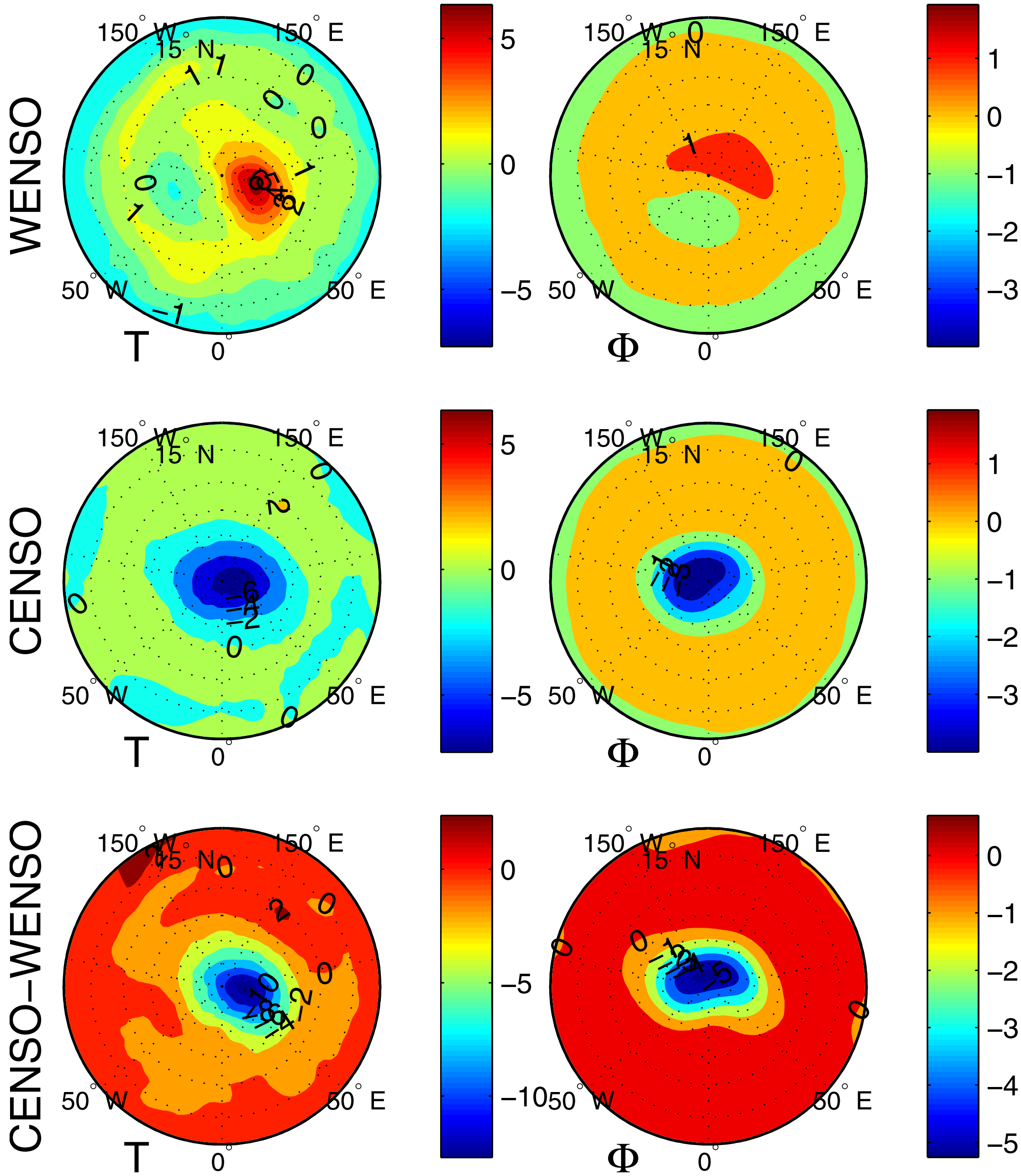

Figure 5. Temperature and geopotential anomalies at 10 mbar in the NH during NDJF under WQBO conditions composited according to the phase of ENSO (limit combination: QBO > 0.6, |ENSO| > 0.8).

magnitude of the temperature and geopotential anomalies are smaller in EQBO but larger in WQBO.

5.2. Effects of ENSO Under Near-Neutral QBO

[37] Performing an analysis similar to the above except taking ENSO months that are QBO-neutral is difficult. It was relatively easy to take QBO under neutral ENSO because the Nino3 index is approximately Gaussian and thus the probability of it being between -0.5 and 0.5 is large. The QBO index, on the other hand, is fundamentally bimodal (see Figure 2; the bimodality is enhanced higher in the stratosphere) and thus is almost always present as an influence on the circulation.

[38] A table similar to others in this paper evaluating significance of the difference in the means between WENSO and CENSO under neutral QBO is not included as significance is not achieved at 95%. The few ENSO non-QBO months that did occur mostly happened during WENSO, and not CENSO, for a wide range of limit combinations. Table 2 shows that WENSO under neutral QBO months are significantly warmer than climatology during NDJF. Significance is maintained even if volcanic and presatellite era data is removed, as seen in Table 2b and Table 2c. The magnitude of the signal actually grows when the composite is restricted to NDJ, indicating that our results are not contaminated by the solar cycle effect in February.

[39] Figure 3 shows the geopotential and temperature anomalies for the composites of CENSO and WENSO for the case of |ENSO| > 0.7 and |QBO| < 0.5. There have been

Table 4a. CENSO/WQBO Versus CENSO/EQBO in the Arctic in ONDJ[a]

	ENSO < −0.4	ENSO < −0.8	ENSO < −1.1
$\vert$QBO$\vert$ > 0.4	−**2.9**,70,−4.7,43,35	−**1.9**,48,−3.7,35,19	−**2.5**,26,−8.0,22, 8
$\vert$QBO$\vert$ > 0.7	−**3.3**,64,−5.4,38,34	−**2.3**,43,−4.6,31,18	−**2.8**,25,−8.7,21, 8
$\vert$QBO$\vert$ > 1.0	−**2.0**,48,−3.9,23,31	−1.4,29,−3.0,16,18	−**2.0**,15,−6.5,11, 8

[a]Same as Table 1, except the third number is the difference between the mean of WQBO and EQBO, the fourth number is the number of WQBO months that fit the requirements, and the last number is the number of EQBO months that fit the requirements.

11 WENSO months and 8 CENSO months satisfying this limit combination over the 50 years of data. The WENSO signal is zonally symmetric at the 10 mbar level. If this plot is reproduced at the 30 mbar level, the warming in WENSO is less zonally symmetric and more like wave number 1. In addition, the cooling in CENSO, which is barely existent at 10 mbar, is more evident at 30 mbar; it also looks like wave number 1, but with the regions of warming/cooling in WENSO regions of cooling/warming in CENSO.

6. Analysis of ENSO/QBO for Nonneutral QBO/ENSO

[40] This section will endeavor to isolate the effects of ENSO and the QBO through the study of 4 different composites: WENSO/WQBO, WENSO/EQBO, CENSO/EQBO, and CENSO/WQBO. A month is placed into one of these four categories if the ENSO and QBO indices exceed a certain amount. Each of these four are compared to the two that have the opposite phase for only one of its indices, for a total of 4 comparisons (that is, on Figure 4, no diagonal comparisons are made, only the two vertical and two horizontal). For the Antarctic, one diagonal comparison is made. The Student t difference of means test is used.

6.1. Arctic

[41] Composites for the 4 categories mentioned above are created for a range of limits. These four categories are then compared to each other. We cannot attain significance for individual calendar months. Thus a composite of all months with similar expected response is used. As mentioned in section 2, for comparisons where QBO is held constant but ENSO is changed, the core of the winter season, November–February (NDJF), is examined. For comparisons where ENSO is held constant but QBO is changed, the late fall/early winter season, October–January (ONDJ) is examined. Two of the four comparisons give significant results, and for these two, a more detailed analysis is performed.

6.1.1. WENSO/EQBO Versus CENSO/EQBO: Determining the Effect of ENSO When Only EQBO Months Are Included

[42] The months of NDJF are composited together, and a t-test of the difference between the means is taken. The limits are individually ranged from 0.4 up to 1.2 for QBO and 0.4 up to 1.0 for ENSO. The signal is nonexistent, indicating that ENSO has a weak and nonsignificant effect when EQBO conditions are prevalent.

Table 4b. Same as Table 4a but Excluding 2 Years After Volcanic Eruptions[a]

	ENSO < −0.4	ENSO < −0.8	ENSO < −1.1
$\vert$QBO$\vert$ > 0.4	−**3.0**,65,−5.1,38,35	−**2.1**,43,−4.3,30,19	−**2.6**,24,−8.5,20, 8
$\vert$QBO$\vert$ > 0.7	−**3.3**,60,−5.7,34,34	−**2.5**,39,−5.2,27,18	−**3.0**,23,−9.3,19, 8
$\vert$QBO$\vert$ > 1.0	−**2.0**,44,−4.2,19,31	−1.5,26,−3.7,12,18	−**2.1**,14,−7.4, 9, 8

[a]As in Table 4a footnotes.

Table 4c. Same as Table 4b but Only Using Satellite Era Data[a]

	ENSO < −0.4	ENSO < −0.8	ENSO < −1.1
$\vert$QBO$\vert$ > 0.4	−**2.8**,33,−5.8,17,21	−**2.1**,20,−5.7,13,11	−**2.4**, 9,−11.0, 8, 4
$\vert$QBO$\vert$ > 0.7	−**2.6**,32,−5.8,16,21	−**2.1**,20,−5.7,13,11	−**2.4**, 9,−11.0, 8, 4
$\vert$QBO$\vert$ > 1.0	−**2.1**,25,−6.1, 9,20	−**1.8**,14,−7.2, 6,11	−**2.3**, 5,−14.3, 4, 4

[a]As in Table 4a footnotes.

6.1.2. WENSO/WQBO Versus CENSO/WQBO: Determining the Effect of ENSO When Only WQBO Months Are Included

[43] The months of NDJF are composited together, and a t test of the difference between the means is taken. A wide range of limits is examined for both QBO and ENSO. See Table 3a for the results. Meaningful results are attained for QBO index up to 0.8, but excluding months with QBO index between 0.6 and 0.8 reduces significance. This decline is consistent with *Naito et al.* [2003], but *Naito et al.* [2003] found that this effect was only relevant for unrealistic WQBO amplitudes. As the ENSO index is raised for a given QBO index, the size of the signal increases. For some combinations of limits, significance exceeding 99.9% is attained. When we remove February from our composites, and only take NDJ, significance is reduced but still is achieved. This indicates that our results are not contaminated by a solar cycle effect in late winter.

[44] To eliminate the possible influence of volcanoes on this result, the two years following a volcanic eruption are excluded. See Table 3b. The mean temperature difference is not systematically changed, but since the number of degrees of freedom is reduced, t scores drop; significance is still achieved, though, for a broad range of limits. Finally, only postsatellite data from 1979 and on is used. This appears in Table 3c. T-scores are further eroded but significance still exists for a range of limits.

[45] Figure 5 shows the temperature and geopotential for the extended winter composite of NDJF for the combination of limits (QBO > 0.6, |ENSO| > 0.8). The anomaly in WENSO is not zonally symmetric. This wave-1 like feature is common to the plots of a wide range of the limit combinations shown in Table 3 that are highly significant (plots not shown). If this same combination of limits is plotted at 30 mbar, the WENSO signal becomes even more wave-1 like, while the CENSO signal stays zonally symmetric but weakens slightly.

6.1.3. CENSO/WQBO Versus CENSO/EQBO: Determining the Effect of QBO When Only CENSO Months Are Included

[46] The sign of the temperature difference between CENSO/WQBO and CENSO/EQBO flips between early winter and late winter so that CENSO/EQBO is warmer in the first half of winter and CENSO/WQBO warmer in the second half. This warming in WQBO in the second half of winter is not significant at 95% and is not investigated further.

[47] The months of ONDJ are composited together, and a t-test of the difference between the means is taken. See

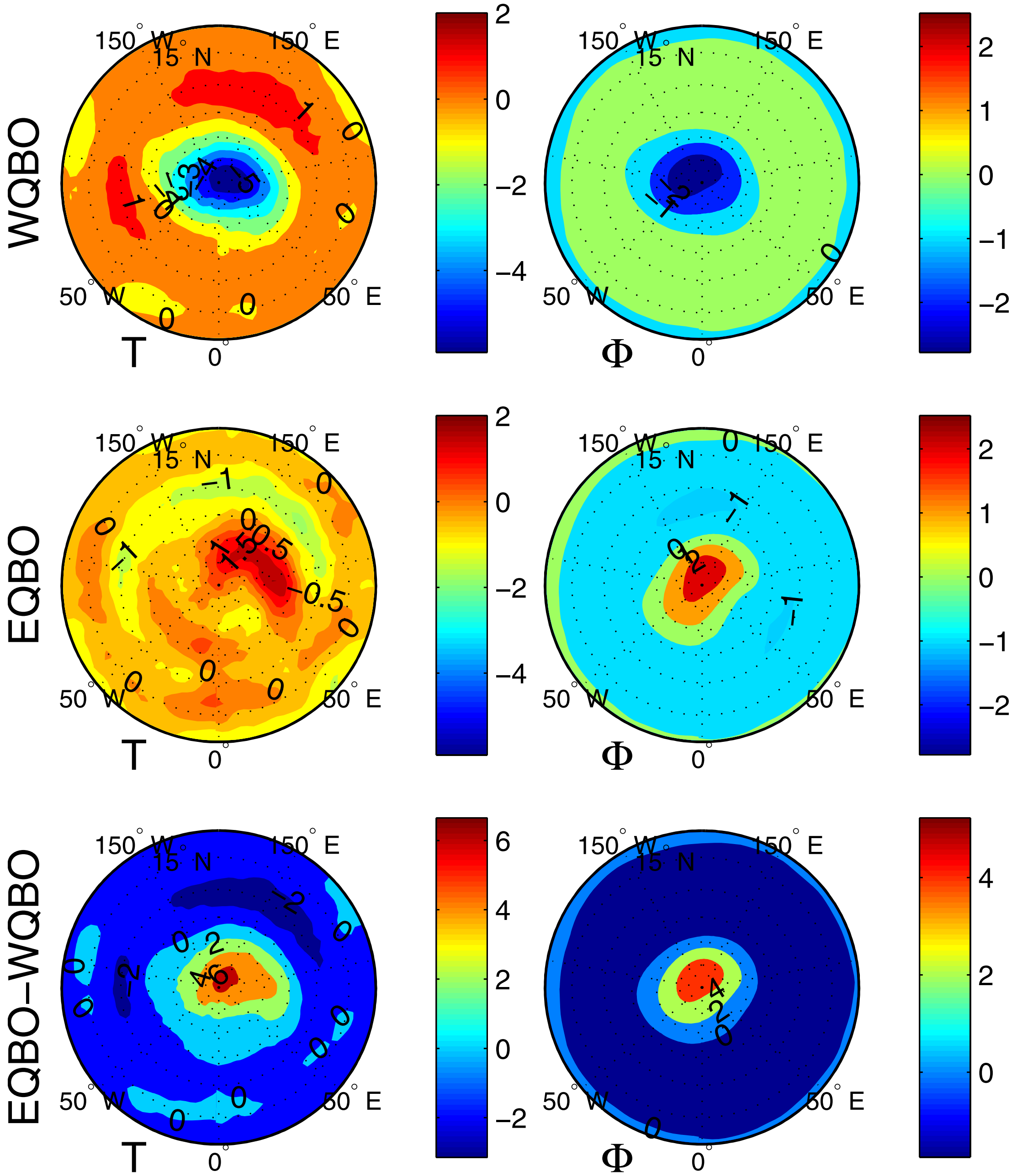

Figure 6. Temperature and geopotential anomalies during ONDJ at 10 mbar in the NH under CENSO conditions composited according to the phase of QBO (limit combination: |QBO| > 0.6, ENSO < –0.8).

Table 4a; a significant difference between EQBO and WQBO exists for a large range of limits. Table 4b excludes months within 2 years of a volcanic eruption. Table 4c includes only satellite era data from 1979 onward. More of the table no longer meets significance at 95%, but most of it does. The size of the signal increases as presatellite era data is removed.

[48] A plot of the temperature and geopotential for the extended composite of ONDJ appears in Figure 6 for the combination of limits (|QBO| > 0.6, ENSO < –0.8). At 10 mbar, the warming in EQBO looks weak, and the cooling in WQBO strong. At 30 mbar, the two are of roughly equal magnitude, with the difference between the two (WQBO-EQBO) still peaking at 6°C. The disturbance anomalies look zonally symmetric at both levels.

6.1.4. WENSO/WQBO Versus WENSO/EQBO: Determining the Effect of QBO When Only WENSO Months Are Included

[49] Similar to the CENSO/WQBO versus CENSO/EQBO comparison above, the sign of the temperature anomalies between WENSO/WQBO and WENSO/EQBO flips between OND and JFM; thus the two periods are evaluated separately. In OND, only combinations of limits with extreme QBO indices are significant at 95%. The

Table 5a. CENSO/WQBO Versus WENSO/EQBO in the Antarctic in OND[a]

	|ENSO| > .4	|ENSO| > .6	|ENSO| > .8
|QBO| > 0.4	−**2.5**,25,−4.4,21,18,−2.2	−**2.1**,21,−4.3,18,15,−2.3	−**2.3**,18,−5.2,14,14,−2.5
|QBO| > 0.6	−**2.5**,22,−4.6,19,16,−2.6	−**2.1**,18,−4.4,16,13,−2.8	−**2.3**,15,−5.5,13,12,−3.1
|QBO| > 0.8	−**2.2**,18,−5.0,13,15,−3.3	−**1.9**,14,−4.9,11,12,−3.6	−**2.0**,13,−5.6, 9,12,−3.2

[a]The first number is the t score of the unfiltered temperature, the second is the number of degrees of freedom, the third is the difference in the temperature between the two, the fourth is the number of WQBO/CENSO months that fit the requirements, and the fifth is the number of EQBO/WENSO months that fit the requirements. The sixth number in Table 5a is the difference in temperature in the low-pass filtered data. The 2 years after volcanic eruptions have not been removed from Tables 5a and 5b.

results are extremely sensitive to the exclusion or inclusion of a given month. In JFM, the warming of WQBO relative to EQBO is not significant at 95% for any combination of limits. QBO has a weak influence on polar temperatures when WENSO conditions prevail; thus no charts or figures are shown.

6.2. Antarctic

[50] A similar analysis can be performed for the Antarctic. The vortex is too stiff and the wave forcing too weak for there to be an effect on the Southern Hemisphere's vortex in midwinter. However, during the spring warming when the vortex is weakened by thermodynamics, QBO and ENSO can modulate the wave driving and the strength of the vortex. Thus the months of the largest influence are October, November, and December, the vortex breakdown season. For a QBO index defined at 20 mbar, a noticeable response is seen in the CENSO/WQBO versus CENSO/EQBO comparison, and in the WENSO/WQBO versus CENSO/WQBO comparison (the same forcings that affected the Arctic most strongly). Both of these comparisons approach significance at 95% for some limits, but the response is weaker in the Antarctic than the Arctic; the other two comparisons in Figure 4 show even less of a difference. Details are not shown.

[51] The comparison WENSO/EQBO versus CENSO/WQBO is made as well. This is a "diagonal" comparison on Figure 4, not made for the Arctic, but included for the Antarctic because the Antarctic response to ENSO and QBO is weaker than the Arctic response. See Table 5. 99% significance is reached for a wide range of limits. The two years after the three major volcanic eruptions have not been removed for Tables 5a and 5b. The sixth element for each limit combination in Table 5a will be discussed below; the other five elements are the same as in earlier tables. See Figure 7 for plots of the temperature and geopotential for limits (|QBO| > 0.6, |ENSO| > 0.8). The signal looks zonally symmetric. If a similar plot is produced for the satellite era data only, the signal in WENSO/EQBO intensifies and the signal in CENSO/WQBO weakens. At 30 mbar, the CENSO/WQBO signal looks more wave-1 like, and both signals are weaker.

[52] Several caveats need to be added before anything is concluded from this. The Antarctic temperature time series exhibits substantial variability at very low frequencies (with a peak at around 15 years^{-1}). To investigate this further, the data is Butterworth filtered to isolate the low-frequency variability. The low-pass filtered data is then subjected to the same compositing done to generate Table 5a. The difference in the temperature anomaly of the low pass filtered data between WENSO/EQBO and CENSO/WQBO is then calculated, and is included in Table 5a as the sixth number shown for each limit combination. If one then compares the third element to the sixth element for each limit combination, it is evident that $\frac{1}{2}$ of the signal observed in the third element of Table 5a is due to the low-frequency signal, not due to any variability that may be associated with ENSO/QBO. Thus the t scores in the first element of Table 5a are overestimates of the variability associated with ENSO/QBO. To test this, a chart similar to Table 5a can be made using the high-frequency complement of the low-pass filtered data. The t scores for such a table are not significant (not shown). The low-frequency variability looks visually distinct from any variation associated with the introduction of satellite data in the 1970s, or the formation of the ozone hole in the 1980s. A second caveat is that excluding/including the volcanic months has a larger influence on the Antarctic than the Arctic (not shown). A third "problem" is that the Antarctic polar vortex temperature seems to not be normally distributed during this season, so t-statistics are not formally valid. The final problem is the high lag one year autocorrelation discussed in section 2. The Arctic does not exhibit any of these complications. These problems cast serious doubt on conclusion drawn from the ECMWF data in the Antarctic at 10 mbar.

[53] ENSO and the 20 mbar QBO might have an effect on the breakdown of the Antarctic polar vortex, but the effect is weaker than the effect on the Arctic vortex. Other sources of data would need to be examined before definitive conclusions could be reached.

7. Discussion and Conclusion

[54] ENSO has an effect on winter stratospheric temperatures at 10 mbar in the Arctic that is independent of the QBO influence. This is apparent when looking at ENSO when QBO is westerly or in its neutral state. When QBO at 50 mbar is in its easterly state, the influence of ENSO seems reduced. The spatial pattern of the response to ENSO at the 10 mbar and 30 mbar levels seems more wave-1 like.

[55] The QBO at 50 mbar also has an effect on late fall stratospheric temperatures at 10 mbar in the Arctic independent of ENSO. This is apparent when looking at QBO both when ENSO is neutral and when ENSO is in its cold

Table 5b. Same as Table 5a but Only Using Satellite Era Data[a]

	|ENSO| > .4	|ENSO| > .6	|ENSO| > .8
|QBO| > 0.4	−1.8,12,−4.7,10,10	−1.5, 9,−4.9, 8, 8	−1.7, 7,−6.1, 6, 7
|QBO| > 0.6	−**2.1**,11,−4.8, 9, 9	−1.9, 8,−5.1, 7, 7	−**2.3**, 6,−6.3, 5, 6
|QBO| > 0.8	−**2.5**, 8,−6.0, 7, 8	−**2.5**, 6,−6.7, 5, 6	−**2.3**, 5,−6.9, 4, 6

[a]As in Table 5a footnotes.

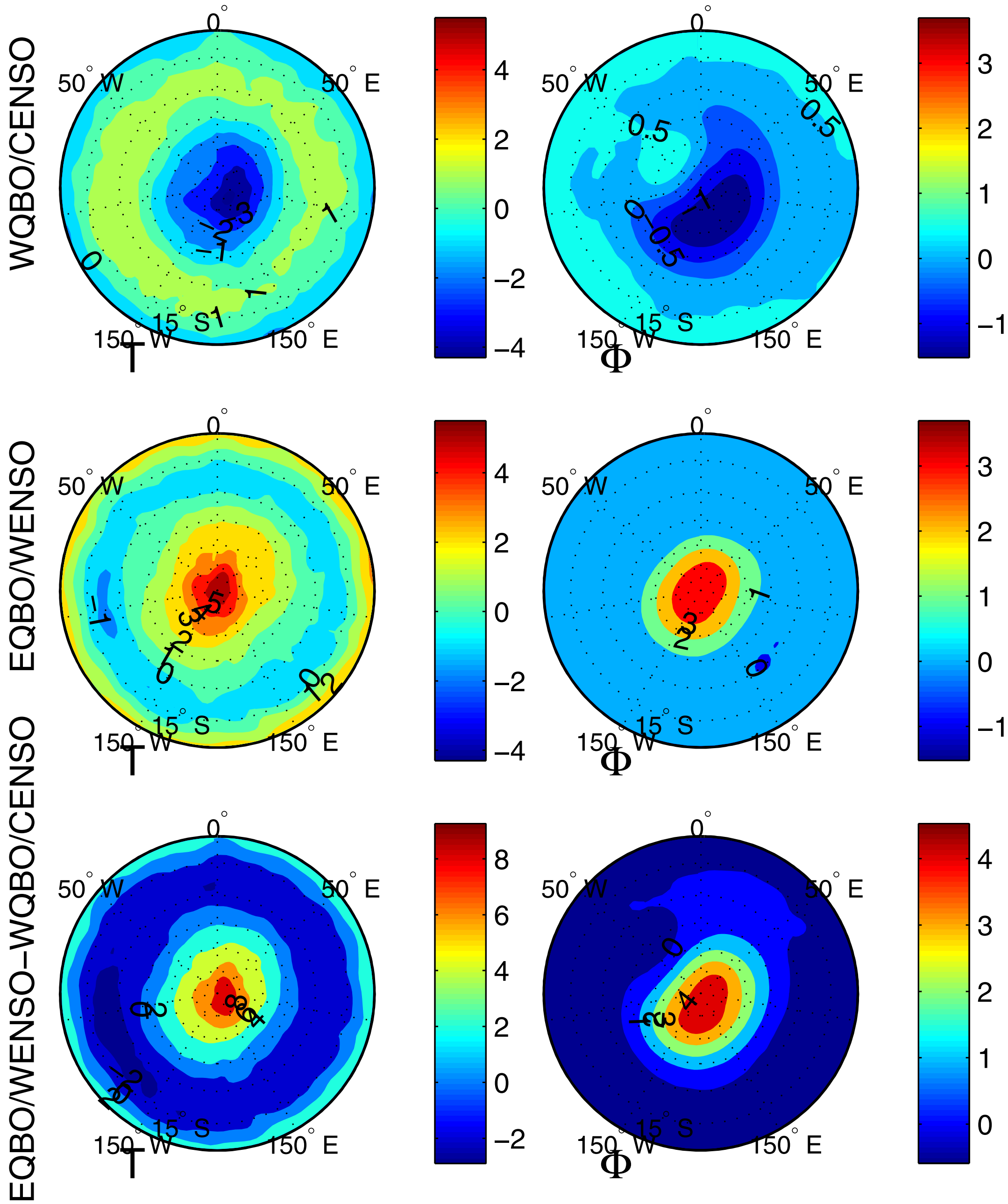

Figure 7. Temperature and geopotential anomalies in OND at 10 mbar under CENSO/WQBO and WENSO/EQBO in the Southern Hemisphere (limit combination: |QBO| > 0.6, |ENSO| > 0.8). The lowest latitude shown is 5°S. The dashed latitude lines are at 15°S, 30°S, 45°S, 60°S, and 75°S.

state. When ENSO is in its warm state, the influence of QBO seems reduced. The spatial pattern of the response to QBO seems to be zonally symmetric.

[56] QBO at 20 mbar and ENSO might also affect the Antarctic polar vortex during the vortex breakdown season, though the effect is smaller than the corresponding effect in the Arctic. No definitive conclusions can be drawn from the data source used.

[57] It is possible to extract an ENSO signal uncontaminated by QBO and a QBO signal uncontaminated by ENSO. The two signals are of comparable magnitude. Results found to be significant for the entire period are also significant for the satellite era, and volcanoes were found to not have much of an effect on these results.

[58] It appears that when you have either WENSO or EQBO conditions, the influence of the other factor is weakened. *Camp and Tung* [2007a] reached similar conclusions when studying the relative effects of the solar cycle and QBO in late winter. When one effect drives the vortex toward a weakened state, the effect of the other factor within this sample is reduced (for example, within WENSO months, the effect of W/E QBO is obscured). This suggests that the response is not linear.

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