Decadal-Scale Changes in the Effect of the QBO on the Northern Stratospheric Polar Vortex

Hua Lu[a,1], Mark P. Baldwin[b], Lesley J. Gray[c], Martin J. Jarvis[a]

[a] *British Antarctic Survey, Cambridge, United Kingdom*

[b] *Northwest Research Associates, Seattle, USA*

[c] *Reading University, Reading, United Kingdom*

Submitted to the Journal of Geophysics Research

November 2007

---

[1]Corresponding author address: Hua Lu, British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK

Email: hlu@bas.ac.uk

Abstract

This study documents decadal-scale changes in the Holton and Tan (HT) relationship, *i.e.*, the influence of the lower stratospheric equatorial quasi-biennial oscillation (QBO) on the northern hemisphere (NH) extra-tropical circulation. Using a combination of ECMWF Re-Analysis-40 and Operational data from 1958-2006, we find that the Arctic stratosphere is indeed warmer under easterly QBO and colder under westerly QBO. During November to January, composite easterly minus westerly QBO signals in zonal wind extend from the lower stratosphere to the upper stratosphere and are centered at ~5 hPa, 55-65°N with a magnitude of ~10 m s^{-1}. In temperature, the maximum signal is near ~20-30 hPa at the pole with a magnitude of ~4K. During winter, the dominant feature is a poleward and downward transfer of wind and temperature anomalies from the mid-latitude upper stratosphere to the high-latitude lower stratosphere.

For the first time, a statistically significant decadal-scale change of the HT relationship during 1977-1997 is diagnosed. The main feature of the change is that the extratropical QBO signals reverse sign in late winter, resulting in fewer and delayed major stratospheric sudden warmings (SSWs), which occurred more often under westerly QBO. Consistent with earlier studies, it is found that the HT relationship is significantly stronger under solar minima overall, but the solar cycle does not appear to be the primary cause for the detected decadal-scale change. Possible mechanisms related to changes in planetary wave forcing are discussed.

1. Introduction

The quasi-biennial oscillation (QBO) in the equatorial stratosphere consists of descending alternating westerly and easterly winds with an average cycle length of ~28 months, varying from 22 months to 34 months [*Reed*, 1965; *Naujokat*, 1986]. Wind direction reversals start near 3 hPa (~40 km), and from this level the QBO phase fronts descend to a dissipation level near 18 km altitude (~90 hPa) with a descent rate of ~1-2 km/month [*Baldwin and Dunkerton*, 1998; *Giorgetta et al.*, 2002]. The oscillation peaks at the equator with a latitudinal half-width of ~12° [*Reed*, 1965]. At individual stations, the QBO has a peak-to-peak amplitude of ~55 m s^{-1} at about 15 hPa, while in the lower stratosphere at 40-50 hPa, the maximum amplitude is about 30 m s^{-1} [*Baldwin and Gray*, 2005].

Studies have been undertaken to understand the QBO influences on the extra-tropical circulation in the stratosphere [*Angell and Korshover*, 1970, 1975; *Dunkerton and Baldwin*, 1991; *Holton and Austin*, 1991; *Baldwin and Dunkerton*, 1998; *Baldwin et al.*, 2001; *Gray et al.*, 2001a; *Naito et al.*, 2003]. Observational studies tend to suggest colder and stronger polar vortex during westerly QBO, warmer and more disturbed polar vortex during easterly QBO. *Holton and Tan* [1980; 1982] proposed a mechanism to explain the phenomenon in terms of planetary wave propagation that is guided by the zero-wind line in the winter subtropics [*Matsuno*, 1970; 1971; *Tung and Lindzen*, 1979]. The rationale is that the vertically propagating stationary planetary waves from the extratropical troposphere can only propagate through a wave-guide of westerly wind. During the easterly QBO phase, the zero-wind line moves to the subtropics of the winter hemisphere. It narrows the width of the planetary wave-guide in the extratropical lower stratosphere. The narrowed wave-guide leads to refraction of the planetary waves away from the subtropical region and consequent redirection poleward. When such wave events with large amplitudes break or dissipate, the resulting additional wave drag slows the polar vortex and warms the polar stratosphere. In extreme cases, they cause major stratospheric sudden warmings (SSWs) [*McIntyre*, 1982]. Conversely, if the QBO is westerly, the waves are less restricted latitudinally, resulting in an anomalously colder and less disturbed polar vortex. Thus, fewer major SSWs occur during a QBO westerly phase. Such QBO influence on the polar vortex through planetary wave propagation is commonly referred to as the Holton-Tan (HT) relationship.

It has been shown that the HT relationship with 'warm disturbed easterly phase' and 'cold undisturbed westerly phase' does not always hold up [*Hamilton*, 1998]. *Labitzke and van Loon* [1988] have suggested that the periods when the HT relationship holds up coincide well with when the 11-year solar cycle is at its minimum but the relationship reverses during solar maximum, although *Gray et al.* [2001b] found that the relationship substantially weakened during solar maximum but that there was no evidence for a reversal. By using National Meteorological Center (NMC) data from 1962-1994, *Naito and Hirota* [1997] found that the HT relationship is statistically significant only for the period of 1962-197; for the entire period of 1962-1994, the HT relationship was statistically significant only in early winter (*i.e.* November and December). *Naito and Hirota* [1997] and *Gray et al.* [2001b] attributed the stronger HT relationship in pre-1977 period to relatively weak solar modulation during the time as it covers one solar maximum and two solar minima, while 1978-1994 period has two solar maxima and one solar minimum. They concluded that the HT relationship holds in early winter and the solar cycle modifies its influence in late winter. By using NCEP/NCAR reanalysis data from 1952 to 2001 at 50 hPa, *Hu and Tung* [2002] repeated the original analysis of *Holton and Tan* [1980]. Similar to *Naito and Hirota* [1997], they found that the HT relationship remains valid in early winter but fails to hold in late winter. However, they concluded that the solar cycle has little effect on wave amplitudes in the lower stratosphere, implying that the solar cycle may not be the responsible factor for the substantially weakened HT relationship in late winter. By using ERA-40 zonal wind from 1979-2001, *Gray et al.* [2004] demonstrated a substantially weakened HT relationship throughout the winter. They found that, although easterly anomalies in the extratropical stratosphere are more likely to be associated with the easterly QBO, the only month in which the HT relationship remains significant at 95% was November.

The discrepancies in the HT relationship were previously attributed to the combination of large interannual variability in the polar region, volcanic eruptions, an overlapping signal with ENSO, the brevity of data and/or limited height range of data sets [*Baldwin et al.*, 2001]. Nevertheless, the evidence in the literature strongly suggests that early and late winter QBO signals in the extra-tropical temperature are different from each other [*Holton and Tan*, 1980; *Naito and Hirota*, 1997; *Hu and Tung*, 2002]. In addition, there may be structural changes in the HT relationship during last 50 years and the 11-yr solar cycle might not be the only modulating factor. However, investigation into other possible modification of the HT relationship is yet to be undertaken.

Given that the largest extratropical QBO signals are found in the NH winter [*Baldwin and Dunkerton*, 1998], this study updates the HT relationship in the NH winter by making an assessment of its seasonal and decadal-scale variation. We examine the relationship between the QBO in equatorial winds and high latitude wind and temperature anomalies at all pressure levels up to 1 hPa. By studying its seasonal progression and identifying the dominant season (*e.g.* early or late winter) when the major changes have occurred, we aim to address three main objectives: 1) to determine if the HT relationship holds up for the period of 1958-2006; 2) to examine whether the HT relationship has weakened or reversed during that period, and 3) to study whether and how the 11-year solar cycle may relate to the decadal-scale changes of the HT relationship.

2. Data and Methods

Our analysis uses monthly-mean wind and temperatures from ECMWF (European Centre for Medium Range Weather Forecasting) ERA-40 Reanalysis (September 1957 to August 2002) and ECMWF Operational analyses (September 2002 to December 2006).

The ERA-40 Reanalysis used ECMWF's 3D variational data assimilation system with a spectral resolution of T159, corresponding to a 1.125° horizontal resolution in latitude and longitude. The model had 60 levels in the vertical between the surface and 0.1 hPa (~65 km). Only the 23 standard pressure surfaces from 1000 hPa to 1 hPa are used here. The data in this height range were assimilated using direct radiosonde and satellite measurements (when available), while the data beyond 1 hPa represent primarily the modeled results [*Uppala*, 2005]. *Baldwin and Gray* [2005] showed that the QBO extracted from ERA-40 is consistent with rocketsonde winds (that were not assimilated) measured at Ascension and Kwajalein up to 2-3 hPa, even for those years before satellite era.

The ECMWF Operational data used ECMWF's 4D variational data assimilation scheme and were output from the ongoing analyses produced by the most recent

ECMWF Integrated Forecasting System (IFS) model. The most recent IFS uses T799 horizontal resolution and 91 vertical levels to 0.01 hPa. The data from October 2002 to the present day are available on the same 1.125º grid and on 21 pressure levels, identical to the ERA-40 data except without the 600 and 775 hPa levels. Rather than using 21 levels for the entire analysis period, we chose to linearly interpolate the Operational data to these missing levels after the data were zonally averaged.

Our correlation and compositing analyses are all carried out using deseasonalized zonal-mean zonal wind and temperature. The deseasonalization is carried out by taking monthly mean values based on the records for the entire period of 1958-2006 at each grid point. Changes in the availability of satellite data and the operational assimilation system, beginning in 2002, mean that the data record, especially near 1 hPa, may have varied in quality.

The 50 hPa zonal wind is chosen to define the phase of the equatorial QBO, in order to be consistent with *Holton and Tan* [1980]. In this study, the equatorial zonal winds are extracted at 0.56 °N, 50 hPa from the combined ERA-40 and Operational records. In fact, 50 hPa winds are the closest to the optimum level suggested by *Baldwin and Dunkerton* [1998], who found that the largest QBO signals were obtained with a QBO defined at 40-50 hPa for the NH, and 20-30 hPa in the SH. The westerly and easterly phases were defined as the deseasonalised monthly zonal-mean zonal wind ≥ 2 m s^{-1} and ≤ -2 m s^{-1}, and are hereafter referred to as w-QBO and e-QBO, respectively. However, we found that other choices of threshold values in the range of ±0-5 m s^{-1} produce similar outcomes, though smaller thresholds result in slightly smaller correlation coefficients while larger thresholds result in higher correlation but with limited numbers of sample points.

A list of the major SSW events occurring during 1958–2001 was compiled recently by *Charlton and Polvani* [2007]. In addition, three major SSW events that occurred after 2001 and before 2007 are identified using the same criteria, *i.e.* Jan., 2003, Jan., 2004, and Jan., 2006 (*Charlton*, personal communication, 2007). All these events are used here to examine whether the e-QBO indeed favours the occurrence of major warmings, as proposed by *McIntyre* [1982], or whether such a QBO-phase *vs* SSW relationship has changed when examined over a longer duration data period.

During 1958–2006, major perturbations to the stratospheric circulation resulted from three major volcanic eruptions – Agung in March, 1963, El Chichón in March, 1982 and Pinatubo in June, 1991. To avoid contamination by the anomalous warming caused by volcanic aerosols in the stratosphere, the 24 months following these major eruptions are excluded from the spatial analysis. However, in order to maintain the temporal continuity in the analyses of the individual time series, these volcanically contaminated data are kept in the analyses presented in Section 3.2. Nevertheless, we found that the overall results are not sensitive to keeping or removing the 24 months data after volcanic eruptions.

The main diagnostic tools employed in this study are correlation studies and composite analysis. Throughout the study, statistical significances are tested using Monte Carlo trial-based non-parametric methods. In Section 3.2, a Monte Carlo trial-based test proposed by *Wang et al.* [2006] is used to determine the significance of the maximum differences of the running correlation coefficients. To perform such a test, we first ensured that the two time series under consideration can be represented satisfactorily by a first-order auto-regressive (AR1) process using the method of *Neumaier and Schneider* [2001]. That is, whether the two time series under consideration can be represented by two AR1 processes $\{X_t\}$ and $\{Y_t\}$ with:

$$
\begin{aligned}
X_t - \mu_X &= \alpha_X (X_{t-1} - \mu_X) + \varepsilon_t \\
Y_t - \mu_Y &= \alpha_Y (Y_{t-1} - \mu_Y) + \eta_t
\end{aligned}
\tag{1}
$$

where (ε_t, η_t) obeys a bivariate normal distribution such that the correlation between ε_t, and η_t is r for any given time t; this implies that, when $\alpha_X = \alpha_Y = \alpha$, the cross correlation between $\{X_t\}$ and $\{Y_t\}$ is $r\alpha^\tau$ at lag τ. Under this condition, a large number of (ε_t, η_t) time series can be generated by Gibbs sampling as correlated pairs of time series, in which the correlation coefficient r is determined by performing a linear correlation between the two time series. The simple AR1 model of (1) is then used to generate a large number (*e.g.* 100,000) pairs of synthetic time series having the same length as the original two time series. This allows the differences between the maximum and minimum values of running correlation to be calculated using a large number of synthetic pairs of the time series. A distribution of the differences can then be constructed accordingly. The difference between the maximum and minimum values of running correlation estimated from the original time series is finally compared to this difference distribution and the rank of this difference among these randomized trials determines its significance level. For simplicity, we call the resulting significance level a p-value, following conventional statistics terminology.

Similar Monte Carlo significance tests are also used to test the statistical significance of the correlation or composite difference between two sub-samples. In both cases, two sub-samples from the original time series with the lengths equal to the two original sub-samples are generated randomly and then the correlation or the difference between their mean values is computed. At each grid point, this procedure is repeated 10,000 times and a distribution of the correlation or the difference is constructed. The correlation or the composite difference between the original sub-samples is then compared to this Monte Carlo simulation generated distribution. The rank of the actual correlation or difference among these randomized trials determines its significance level. We say the correlation or difference within a region is statistically significant if its confidence level within the region are equal to or above 95%.

3. Results

3.1 QBO Composites during Early and Late Winter

Fig. 1 shows the QBO time series at 10 pressure levels from 100 to 1 hPa and from 1958-2006. The descending alternating easterly and westerly winds are the dominant feature of the QBO, particularly between 5-70 hPa, with maximum amplitude at ~40 m s^{-1}. The difference in descent rates of the easterly and westerly shear zones can be clearly seen. A comparison with the corresponding time-series of single station radiosonde data [*Naujokat*, 1986] and rocketsonde data [*Gray et al.*, 2001b] suggests that the QBO is captured exceedingly well up to 2-3 hPa, even in the pre-satellite era in the ERA-40 data [*Baldwin and Gray*, 2005]. As reported by *Punge and Giorgetta* [2007], enhanced westerly winds appear above 10 hPa during the second half of the 1980s and much of the 1990s, suggesting a possible structural change of the QBO in the upper stratosphere. However, no obvious change is discernible around September 1978, implying the upper stratospheric change may not be a direct result of data assimilation pre-/post- satellite era.

[[Insert Fig. 1 here]]

Fig. 2 shows the composites of zonal-mean zonal wind (lined contours) and temperature (color shaded) anomalies for e-QBO (left-hand panels) and w-QBO (right-hand panels), for November to January monthly averages (top panels), and February to March monthly averages (bottom panels) for the entire period of 1958-2006. In November to January and under e-QBO, the easterly anomalies centred at ~60°N, 5 hPa in the extratropical stratosphere are associated with a generally warmer polar vortex extending from 3 hPa to 300 hPa with the centre located at ~90°N, 30 hPa. The opposite holds for the w-QBO composites, in which a stronger, colder stratospheric vortex exists. On average, the extratropical stratospheric winds are up to ~10 m s^{-1} stronger under w-QBO than under e-QBO, while the Arctic stratospheric temperature is up to 3-4 K warmer under e-QBO than under w-QBO.

[[Insert Fig. 2 here]]

During late winter and under e-QBO, the easterly anomaly has moved slightly poleward and downward and is centred near 65°N, 20 hPa. Warming remains below 30 hPa with its center located at ~90°N, 150 hPa. From 60°N poleward, while the lower stratosphere is warmer, the Arctic upper stratosphere is noticeably cooler. The opposite spatial pattern holds for the w-QBO. Thus, the dominant feature of the late winter HT relationship is a downward movement of westerly or easterly winds from the mid-latitude upper stratosphere, and cooling or warming (dependent upon QBO phase) in the Arctic upper stratosphere with an opposite signed cell directly below. Consequently, the HT relationship evolves from early winter to late winter. At a fixed level, the HT relationship appears to change through the winter, because the circulation and temperature anomalies slowly descend.

3.2 Temporal Variations of the QBO and its Extratropical QBO Signals

As the HT relationship is the strongest during winter months and appears to descend slowly during late winter, it would be useful to focus on the whole winter as well as the late winter in order to investigate decadal-scale change of the HT relationship. In this section, we look for systematic temporal changes in correlation coefficients between the equatorial QBO zonal wind time series and extratropical wind and temperature records extracted from three extratropical locations in the stratosphere. In each case, we examine averages for the extended winter period (*i.e.* November to March) and also for the late winter months (*i.e.* February to March).

Fig. 3 shows the Nov-Mar averaged time series of (a) the zonal wind anomaly at 54.4°N, 10 hPa,(b) the temperature anomaly at 65.5°N, 50 hPa and (c) the temperature anomaly at 65.5°N, 200 hPa. On each of the plots the Nov-Mar averaged equatorial QBO has been superimposed (grey lines). For the whole period 1958-2006, the correlation coefficient (r) between the equatorial QBO and the extratropical wind is 0.64, and the correlation coefficients between the equatorial QBO and the two polar temperature time series are −0.50 and −0.57, respectively. These results show that in the NH the vortex is generally stronger and colder under w-QBO and weaker and warmer under e-QBO. The correlations are all significant at a confidence level above 99%, implying that the HT relationship holds for the averaged condition for the extended winter period. They suggest that about 30-40% of the extratropical variations in zonal wind and temperature for the extended winter may be explained by the HT relationship.

There is a noticeable structural change in the QBO averaged over the extended winter period. From the mid-1970s to the mid- or late 1990s, the QBO preferentially appears in its westerly phase more than in its easterly phase. During 1975-1995, for instance, only 1979, 1984 and 1989 are clearly e-QBO. Such a structural change can also be demonstrated through its correlations with the extratropical time series. More specifically, we found substantially weakened correlations during 1977-1997 with $|r| < 0.3$) and confidence levels below 80%. In both wind and temperature, the high correlations evident in the first and last sub-periods are not present during 1977-1997. These changes appear to have affected a large vertical range.

[[Insert Fig. 3 here]]

Fig. 4 shows the same as Fig. 3 but here the averages are taken for February and March only. Though the structural change in the equatorial QBO itself becomes less clear, the differences between the correlation coefficients and confidence levels for the first and last sub-periods and for the mid-period of 1977-1997 become even larger. For instance, in both 1958-1976 and 1998-2006 periods, the correlation coefficients are positive for wind and negative for temperature while the reverse is true for 1977-1997. The correlations are statistically significant at confidence levels above 99% only in 1958-1976. We found that the sub-period differences in correlations associated with November to January months are considerably smaller (not shown). Thus, late winter changes are primarily responsible for the substantially weakened HT relationship during 1977-1997. An additional new result is that, over the whole period of 1958-2006, the QBO signature in the extratropical temperature is actually stronger in the lowermost stratosphere (*i.e.* 200 hPa) than at its conventional height of 50 hPa.

[[Insert Fig. 4 here]]

To demonstrate the magnitude of the change more systematically, running correlation coefficients for the all cases shown in Figs. 2 and 3 over blocks of data spanning 21 years are computed and are shown in Fig. 5. The 21-year length of the running window is chosen to ensure a degree of statistical stability in the estimated correlations, while providing some localization in time. We verified that qualitatively similar results are obtainable by using a running correlation window from 17 to 25 years.

The left-hand panels of Fig. 5 show the running correlation coefficients for the three cases where the data are averaged over November to March. In each panel, the range (maximum minus minimum) of correlation coefficients is 0.56, 0.75 and 0.64, respectively. The right-hand panels of Fig. 5 show that a similar change in the HT relationship is maintained for Feb-Mar averages. The ranges are 0.94, 0.81 and 0.81, respectively, which are larger than those associated with Nov-Mar averages. Around 1985, the correlation changes from positive to negative for the winds and from negative to positive for the temperatures. All six running correlation curves peak or trough around 1987 and share an essentially similar shape.

The hypothesis of a systematic temporal change in the HT relationship needs to be tested objectively. The null hypothesis we assume here is that there is no temporal structure change in the HT relationship and the observed variations in the running correlation shown in Fig. 5 are merely due to statistical fluctuations. First of all, using the method proposed by *Neumaier and Schneider* [2001], our fitting results suggest that good models for both the equatorial QBO and the NH extratropical time series are stochastic AR1 processes. It allows us to perform the significance test proposed by *Wang et al.* [2006] and a p-value is generated for each correlation case. In relation to the null hypotheses under consideration here, the p-value is large if the observed range of running correlation could reasonably occur by chance, and small if the observed range is unlikely to occur by chance. A p value of 0.05 corresponds to the 95% confidence level.

[[Insert Fig. 5 here]]

The *p*-values for the differences in running correlations between the QBO and extratropical wind and temperature anomalies are 0.201, 0.065 and 0.106 for the cases of Nov-Mar mean. None of these results is statistically significance at the 95% level. The Feb-Mar mean results are 0.014, 0.046 and 0.045, respectively. The evidence for the late winter mean is stronger across all three time series as the *p*-values are all below 0.05, allowing us to reject the null hypothesis with greater than 95% confidence.

Though we find here that the decadal-scale changes in the HT relationship during late winter is statistically significant, it still leaves room for other factors, such as the effect of internal atmospheric variability or the 11-yr solar cycle, to cause temporal structured fluctuations in the HT relationship. Ultimately, longer data series will provide a more concrete conclusion.

3.3 Seasonal Progressions of Composite Differences

In this section, the spatial and seasonal variations of the HT relationship are studied to determine whether or not the variation in HT relationship shown in section 3.2 is a property that applies only to certain pre-selected locations. Latitude/height composite analyses are performed for the entire period of 1958-2006 first. The composite analysis for the first and last sub-periods (*i.e.*1958-1976 & 1998-2006) is then performed as a single data group, and the results are compared with those for the middle period (1977-1997).

Fig. 6 shows the seasonal progression of the QBO composite differences (*i.e.* e-QBO – w-QBO) of the zonal-mean zonal wind anomalies in vertical-meridional cross section from October to April for the NH. The 1st, 2nd, and 3rd columns are for the whole period (1958-2006), the combined two end sub-periods (1958-1976 & 1998-

2006) and the middle period (1977-1997), respectively. The areas within the grey contours represent statistical significances at confidence levels equal or greater than 95%.

[[**Insert Fig. 6 here**]]

For the period of 1958-2006 (1st column), a three-cell vertical structure of the QBO, similar to that shown by *Pascoe et al.* [2005], is evident in the tropics. From October to March, negative wind differences can be observed in the Arctic stratosphere, implying a more disturbed polar vortex with persisting easterly equatorial anomalies near 50 hPa during winter months. The data suggest that the easterly anomalies first originate in the upper stratospheric subtropics at 22°N, 3-5 hPa during September (not shown). From November to January, these easterlies are enhanced and move poleward. Its downward movement starts in late winter months from February to March. During those movements, the center of the easterlies shifts slightly from 50−55°N, 1−5 hPa to 55−65°N, 5−10 hPa. By April, the easterlies appear to have descended into the troposphere. These QBO composite differences primarily feature the characteristics of typical e-QBO composites, with a smaller contribution from w-QBO composites (not shown). Overall, the extratropical QBO signals are stronger in early winter (*i.e.* Nov-Jan) and weaker in mid- to late winter (*i.e.* Feb-Mar).

For the combined 1958-1976 & 1998-2006 periods (2nd column of Fig. 6), the overall QBO signal patterns are quite similar to those during 1958-2006, but with much stronger easterlies in the Artic stratosphere. In comparison to those for 1958-2006, notably larger magnitudes of the easterlies are observable in December and March. The QBO signals can be found during most of the winter months in the Arctic stratosphere, except for January. Slight poleward and downward movement of the easterlies can be observed as winter progresses.

For the 1977-1997 period (3rd column of Fig. 6), the extratropical QBO composite differences are distinctly different from the other two columns in the extratropics. Easterly anomalies appear in the extratropical stratosphere in November to January and reverse into westerlies in February through April. This suggests a strengthened polar vortex under e-QBO which moves poleward and downward. During this period, the typical extratropical HT QBO signature can only be found in November.

[[**Insert Fig. 7 here**]]

Fig. 7 shows the corresponding QBO composite differences in temperature. During 1958-2006 (1st column of Fig. 7), the tropical and mid-latitude QBO signals show a well-defined pattern of the QBO-induced secondary circulation, which is connected by meridional and vertical positive/negative temperature anomaly cells. At mid-latitudes, a three-cell structure in height at the equator is present with warming in the upper stratosphere (~ 4 K), cooling in the lower to mid- stratosphere (~ −3 K) and weaker warming in the lowermost stratosphere (~ 0.3 K). Those maxima are centered at heights of about 3 hPa (40km), 30 hPa (25 km) and 200hPa (11 km). The Arctic lower stratosphere is anomalously warmer by up to 4 K throughout the winter. During February, however, the mid- to upper stratosphere (1-10 hPa, 65-90°N) is colder (by up to 13 K). Overall, positive QBO signals in temperature are found in the upper mid-latitude stratosphere as well as the Artic lower stratosphere, while negative QBO signals are found at mid-latitudes of the middle stratosphere.

For the combined 1958-1976 & 1998-2006 periods (2nd column of Fig. 7), the tropical to mid-latitude QBO signals remain very much the same as those for 1958-

2006. In the Arctic stratosphere, up to 10 K temperature differences can be observed during December. The positive QBO signals in the Arctic lower stratosphere are noticeably stronger during late winter.

For the 1977-1997 period (3rd column of Fig. 7), the tropical QBO signals are similar in sign to those for 1958-2006, as would be expected because of the way in which the e-QBO and w-QBO years are defined. However, the magnitudes of cooling in the tropical lower and upper stratospheres are ~1-2 K smaller and they are barely significant at a 90% confidence level. In early winter, the three-cell structure in the subtropics to mid-latitudes remains, with warming in the upper stratosphere (15−40°N, 1−10 hPa), cooling in the lower to mid- stratosphere (15−50°N, 10−100 hPa) and lesser warming in the lower most stratosphere (20−30°N, 100−200 hPa). Although such structure remains during late winter, they become substantially weakened and are not significant even at the 90% confidence level. In the extratropics, there is a suggestion of weak warming in the winter months, which is only observable in the lowermost stratosphere of the Arctic. Cooling, on the other hand, is visible in the lower stratosphere during March.

Theoretical studies have suggested that the QBO influence on temperature is a result of downward and upward motion associated with the QBO-induced meridional circulation [*Plumb and Bell*, 1982]. This is consistent with the warming and cooling structure resulting from the wave-induced transfer of easterly/westerly momentum to the mean flow in the high-latitude stratosphere [*Garcia*, 1987; *Gray and Pyle*, 1989]. The QBO-induced meridional circulation starts at the equator and is balanced by upward and downward motion in the subtropics and mid-latitudes, and these are then balanced by downward and upward motion in the polar region. Such a general pattern of dynamic influences of the QBO is shown clearly in most of the panels of Figs. 5

and 6, except for those for 1977-1997, particularly during late winter. This suggests possible regime shifts around 1977 and 1997.

3.4 Decadal-scale Change of the Major SSWs

McIntyre [1982] suggested that the HT relationship may affect the likelihood of the SSWs. That is, the easterly winds present in the subtropics during e-QBO years may act as a wave-guide and hence may favor the occurrence of a major SSW. In this section, we examine the occurrence of SSWs to investigate whether a coherent temporal change in the occurrence frequency of major SSWs is evident.

[[Insert Fig. 8 here]]

Fig. 8 shows the distributions of major SSW events grouped for the periods of 1958-2006, 1958-1976, 1977-1997 and 1998-2006. In total, 33 SSW events occurred in 1958-2006, *i.e.* 33 events in 49 years, averaging 0.67 SSWs per year. In the whole period 1958-2006, there is no clear preference for either phase of the QBO; the occurrence ratio is 15:16 between e-QBO and w-QBO. For the three consecutive sub-periods, the average number of major SSWs per year is 0.74 per year (14/19), 0.43 (9/21) and 1.11 (10/9), respectively. Thus, the major SSWs have occurred less frequently during 1977-1997.

Differences in occurrence patterns can also be observed when the major SSWs are grouped according to the phases of the QBO. For the entire period of 1958-2006, there are more major SSWs occurring under e-QBO in early winter but the opposite holds in mid- to late winter. In 1958-1976, 9 out of 14 events occurred under e-QBO, reinforcing the concept of a strong influence of the HT relationship. However, during 1977-1997, only 2 out of 9 events occurred under e-QBO, suggesting either a weakened or even a reversed HT relationship. During this period, noticeably more events occurred in late winter rather than in mid-winter, implying a significant delay in the timing of major SSWs. In 1998-2006, an approximately equal number of major SSWs occurred under the two QBO phases (*i.e.* 5:6), though more events occurred under e-QBO in early winter and under w-QBO in mid- to late winter.

It is not clear from this dataset why the occurrence of SSWs appears to be influenced by the phase of the QBO in some periods but not in others. One possibility, suggested by *Dunkerton et al.* [1988] is that the existence of a deep layer of equatorial easterlies or westerlies is more important than easterly or westerly winds at any single level. More events (or modelling studies) are needed in order to investigate this.

3.5 11-yr Solar Cycle Modulation

Another possible influence on the frequency of SSWs is the 11-yr solar cycle(SC), which could influence SSWs directly by the presence of a SC wind anomaly in the subtropical upper stratosphere [*Kodera and Kuroda*, 2002; *Gray et al.*, 2004] or indirectly by modifying the equatorial QBO [*Salby and Callaghan*, 2000; *McCormack*, 2003; *Pascoe et al.*, 2005]. Previous studies have shown that the strongest apparent SC modulation in the NH occurs in January and February [*Labitzke and van Loon*, 1988; *Labitzke et al.*, 2006]. In this section, using the extended data from 1958 to 2006, we examine if the 11-yr solar cycle indeed modulates the QBO influences in the extra-tropical stratosphere and if it is the responsible factor for the decadal-scale change of the HT relationship.

Fig. 9 shows the correlations between Jan-Feb mean equatorial QBO at 50 hPa and Jan-Feb zonal-mean zonal wind anomalies (1st row), and Jan-Feb temperature anomalies (2nd row). The 1st column shows data for all years, the 2nd and 3rd columns show solar maximum (HS) and solar minimum (LS) years respectively. For the latter columns, the years were grouped when Dec-Feb mean F10.7-cm solar radio flux (F_s) is high (HS) and low (LS) respectively. HS (LS) years are defined as when the standardized F_s is > (<) than 0.2 (–0.2). The three conditions under consideration are referred to as all-data, HS and LS hereafter.

[[Insert Fig. 9 here]]

As shown in previous studies [*Labitzke and van Loon*, 1988; *Naito and Hirota*, 1997; *Gray et al.*, 2001b; *Gray et al.*, 2004], Fig. 9 suggests that the HT relationship fails to hold both when all data are used and under HS, but becomes significant at a confidence level of 95% under LS. Under LS, significant positive correlations are present in the high latitude wind fields while negative QBO signals occur at mid-latitudes. Up to 40% of the variations in the extratropical mid- to lower stratosphere can be accounted for by the HT relationship during LS years. However, during HS years this value falls to only 16% or less, showing that the HT relationship is substantially disturbed during solar maximum.

If solar modulation were the primary cause for the QBO signals pre- and post-1977, then, for a given solar phase, correlation patterns should remain approximately the same across different periods. However, we found that, under LS, the extratropical QBO signals are substantially enhanced and up to 70-80% of the variations in the stratospheric polar winds and temperature can be accounted for by the QBO alone if only the data from 1958-1976 are used (not shown). In 1977-1997, however, the HT relationship is weaker and not significant under all data, HS and LS. For a given solar phase, nearly the same numbers of data samples exist in 1958-1976 and in 1977-1997, implying that there is no clear bias towards HS or LS for these two sub-periods under investigation. Thus, the 11-yr solar cycle does not appear to be the responsible factor for the considerably weakened HT relationship during 1977-1997.

4. Discussions

The results presented here provide additional observational analyses to previous findings from observational [*Baldwin and Dunkerton*, 1991, 1998; *Baldwin et al.*, 2001], theoretical [*Plumb and Bell*, 1982; *Haynes*, 1998] and modeling [*Dunkerton*, 1985; *Gray and Pyle*, 1989] studies. Early studies suggested that the vertical structure of the QBO circulation is a two-cell structure symmetrically straddling the equator. The latitudinal structure of QBO circulation consists of a rising or sinking motion over the equator compensated by an opposing circulation over the subtropics to mid-latitudes, which gives rise to a temperature anomaly in this nearby region that has an opposite sign to that at the equator. However, *Gray et al.* [2004] and *Pascoe et al.* [2005] demonstrated clearly that the vertical pattern of equatorial zonal wind anomalies is in fact a three-cell structure, with an additional cell in the upper stratosphere. Here, we have confirmed that this oscillating pattern of the QBO extends vertically into the upper stratosphere as a three-cell structure both near the equator and in the subtropics. These results are also consistent with recent analysis from satellite measurements [*Huang et al.*, 2006]. It also agrees with the theoretical work of *Plumb and Bell* [1982], who suggested that the meridional circulation provides communication between the equatorial thermal structure and the dynamics at higher latitudes.

Gray et al. [2001b; 2004] suggested that the influence of the QBO wind anomaly in the upper stratosphere may influence the propagation of planetary waves, in addition to the more well-known influence of the QBO wind anomalies in the equatorial lower stratosphere. *Punge and Giorgetta* [2007] diagnosed structure changes of the QBO in the ERA-40 dataset above 5 hPa in the mid-1980s and thereafter. Those changes may have had a profound influence on the extratropics and may somehow contribute to the decadal-scale change of the HT relationship discovered here, by influencing the propagation of planetary waves in the stratosphere. A further possibility is that the nature of the planetary waves generated in the troposphere has altered. The ultimate origin for the abrupt changes around 1977 and 1997 in the HT relationship must originate primarily from changes in planetary wave activity or changes in the stratospheric wave-guide conditions, or most likely a combination of both.

In the past ~25 years, the chemical composition of the stratosphere has changed substantially due to anthropogenic greenhouse emissions and ozone-depletion. The concentration of ozone-depleting substances such as chlorofluorocarbons (CFCs) has begun to stabilizing since the mid-1990 following the successful implementation of the Montreal Protocol [*Weatherhead*, 2000]. Simulations from coupled chemistry-climate models suggest that the ozone recovery rates may contribute to the increase in the strength of the Brewer-Dobson (BD) circulation, which may, in turn, be influenced by increases in greenhouse gas concentrations [*Austin and Wilson*, 2006]. GCM simulations also suggest that enhanced BD-circulation leads to weaker westerly winds and higher than average temperatures in the extratropics during late winter and spring [*Butchart et al.*, 2006]. A weakened westerly wave-guide may reduce the amount or/and the amplitude of the upward propagation planetary waves. Consequently, it may reduce the differences in wave-guide condition between the two QBO phases, thus reducing the effect of the HT relationship.

It is known that vertically-propagating planetary waves from the troposphere control the intensity of the equator-to-pole transport of stratospheric ozone by the BD circulation and thereby modulate the total ozone content at mid- and high-latitudes. For instance, *Hu and Tung* [2003] suggested that changes in stratospheric ozone may lead to an anomalously induced temperature gradient between mid- and high latitudes. This would modify the refraction of planetary waves and thereby either suppress or enhance the propagation of planetary waves into the stratospheric polar region, which then could lead to anomalous cooling or warming in the polar region. *Nathan and Cordero* [2007] found that wave-induced ozone heating can increase wave drag by more than a factor of two in the photochemically controlled upper stratosphere and decrease it by 25% in the dynamically controlled lower stratosphere, suggesting a nonlinear coupling between planetary waves and ozone.

Although the changing chemical composition of the stratosphere is likely to have affected the wave-guide, and therefore the HT relationship, we suggest that these changes have been too gradual to provide a primary explanation for the observed shifts near 1977 and 1997.

The weakening of the HT relationship seems also to be synchronous with changes near the surface. Regime shifts occurring in the mid-1970s and the mid-1990s have been a focus of many investigations regarding climate changes in the North Pacific region [*Nitta and Yamada*, 1989; *Deser and Blackmon*, 1995; *Yasuda and Hanawa*, 1997]. Since the early 1990s, empirical evidence has begun to suggest that a major climate regime shift took place in the mid-1970s, with widespread consequences for the biota of the North Pacific Ocean and Bering Sea [*Hare and Mantua*, 2000]. Recent literature has also suggested another possible regime shift in 1997/1998 in these regions [*Minobe*, 2002; *Rodionov and Overland*, 2005]. A predominant feature of the 1976/1977 regime shift is that the sea surface temperature (SST) difference pre- and post 1977 has two action centers dominated by the Arctic and tropical air mass [*Nakamura et al.*, 1997]. They found that the climate variability around the North Pacific subtropics exhibits strong negative simultaneous correlation with the tropical

SST variability, while changes near the North Pacific sub-Arctic in the mid-1970s cannot be attributed to the tropical influence. The sub-Arctic front became substantially warmer with weakened surface westerlies before mid-1970s and colder with enhanced westerly winds afterward. The enhanced surface westerlies reinforce the underlying SST anomalies, resulting in an increase in the intensity and regularity of warm phases of ENSO. Those near surface changes may alter the relative location or reduce the intensity of the waves propagating into the stratosphere. Recent studies [*e.g. Manzini et al.*, 2006; *Taguchi and Hartmann*, 2006] have shown a link between ENSO and SSWs, which could potentially disrupt the HT relationship.

The HT relationship may have been affected by these regime shifts near the surface through changes in planetary waves and wave propagation. Though it is beyond the scope of this paper, possible decadal changes of planetary wave activity could provide at least part of the reason for the observed regime shifts. The identification of specific tropospheric or stratospheric causes of changes to planetary wave activity may prove to be difficult because the stratosphere and troposphere behave as a coupled system.

5. Conclusions

We have re-examined the Holton and Tan (HT) relationship using 49-year ERA-40 and ECWMF Operational combined data. Our findings are:

1. The HT relationship holds in general for the period of 1958-2006, confirming that the QBO-planetary wave mechanism plays an important role in the Arctic dynamics. During November to January, consistent positive or negative QBO signals extend throughout the stratosphere. They are centered at ~5 hPa, 55-65°N with a magnitude of ~10 m s^{-1} in zonal-mean zonal wind, and at ~20-30

hPa at the pole with a magnitude of ~4K in temperature. In late winter, the dominant feature is a downward movement of westerly or easterly wind anomalies from the mid-latitude upper stratosphere, and cooling or warming in the Arctic upper stratosphere with an opposite-signed cell directly below.

2. The downward movement of the extratropical QBO signals between early and late winter explains why different HT relationships were found and reported for a fixed pressure level [*Holton and Tan*, 1980; *Naito and Hirota*, 1997; *Hu and Tung*, 2002]. At mid-to lower stratosphere at 30-50 hPa, the HT relationship is stronger during early winter and weaker during late winter. In the lowermost stratosphere, the HT relationship holds generally true for the entire winter. In the upper stratosphere, such as 2-3 hPa, the HT relationship is strong but reversed in late winter but weak in early winter.

3. The HT relationship has not been stationary over time. It was substantially weakened in 1977-1997. The timing of the weakening seems to be synchronous with the climate regime shifts over the North Pacific, with possible additional influences from the changes associated with stratospheric ozone depletion.

4. During these 49 years (*i.e.* 1958-2006), the HT relationship in the NH mid-winter fails to hold during the maximum phase of the 11-yr solar cycle. This is consistent with the previous findings [*Labitzke and van Loon*, 1988; *Gray et al.*, 2001b; *Labitzke et al.*, 2006]. However, the 11-yr solar cycle does not appear to be the primary responsible factor for the decadal-scale change during 1977-1997.

6. References

Angell, J.K., and J. Korshover, Quasi-biennial, annual, and semiannual zonal wind and temperature harmonic amplitudes and phases in the stratospheric and low mesosphere of the Northern Hemisphere, *Journal of Geophysical Research*, *75*, 543-550, 1970.

Angell, J.K., and J. Korshover, Evidence for a quasi-biennial variation in the eccentricity of the north polar vortex, *Journal of Atmospheric Sciences*, *32*, 634-635, 1975.

Austin, J., and R.J. Wilson, Ensemble simulations of the decline and recovery of stratospheric ozone, *Journal of Geophysical Research*, *111*, D16314, doi:10.1029/2005JD006907, 2006.

Baldwin, M.P., and T.J. Dunkerton, Quasi-biennial oscillation above 10 MB, *Geophysical Research Letters*, *18*, 1205-1208, 1991.

Baldwin, M.P., and T.J. Dunkerton, Biennial, quasi-biennial, and decadal oscillations of potential vorticity in the northern stratosphere, *Journal of Geophysical Research*, *103* (D4), 3919-3928, 1998.

Baldwin, M.P., and L.J. Gray, Tropical stratospheric zonal winds in ECMWF ERA-40 reanalysis, rocketsonde data, and rawinsonde data, *Geophysical Research Letters*, *32* (9), art. no.-L09806, 2005.

Baldwin, M.P., L.J. Gray, T.J. Dunkerton, K. Hamilton, P.H. Haynes, W.J. Randel, J.R. Holton, M.J. Alexander, I. Hirota, T. Horinouchi, D.B.A. Jones, J.S. Kinnersley, C. Marquardt, K. Sato, and M. Takahashi, The quasi-biennial oscillation, *Reviews of Geophysics*, *39* (2), 179-229, 2001.

Butchart, N., A.A. Scaife, M. Bourqui, J. de Grandpre, S.H.E. Harem, J. Kettleborough, U. Langematz, E. Manzini, F. Sassi, K. Shibata, D. Shindell, and M. Sigmond, Simulations of anthropogenic change in the strengthof the Brewer–Dobson circulation, *Climate Dynamics*, *27*, 727-741, doi:10.1007/s00382-006-0162-4, 2006.

Charlton, A.J., and L.M. Polvani, A new look at stratospheric sudden warmings. Part I. climatology and modelling benchmarks, *Journal of Climate*, *20*, 449-469, 2007.

Deser, C., and M.L. Blackmon, On the relationship between tropical and North Pacific sea surface temperature variations, *Journal of Climate*, *8*, 1677-1680, 1995.

Dunkerton, T.J., A two-dimensional model of the quasi-biennial oscillation, *Journal of Atmospheric Sciences*, *42*, 1151-1160, 1985.

Dunkerton, T.J., and M.P. Baldwin, Quasi-biennial modulation of planetary wave fluxes in the Northern hemisphere winter, *Journal of Atmospheric Sciences*, *48*, 1043-1061, 1991.

Dunkerton, T.J., D.P. Delisi, and M.P. Baldwin, Distribution of major stratospheric warmings in relation to the quasi-biennial oscillation, *Geophysical Research Letters*, *15* (2), 136–139, 1988.

Garcia, R.R., On the mean meridional circulation of the middle atmosphere, *Journal of Atmospheric Sciences*, *44*, 3599-3609, 1987.

Giorgetta, M.A., E. Manzini, and R. E., Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves, *Geophysical Research Letters*, *29* (8), 1245, doi:10.1029/2002GL014756, 2002.

Gray, L.J., S. Crooks, C. Pascoe, S. Sparrow, and M. Palmer, Solar and QBO influences on the timing of stratospheric sudden warmings, *Journal of the Atmospheric Sciences*, *61* (23), 2777-2796, 2004.

Gray, L.J., E.F. Drysdale, T.J. Dunkerton, and B.N. Lawrence, Model studies of the interannual variability of the northern-hemisphere stratospheric winter circulation: The role of the quasi-biennial oscillation, *Quarterly Journal of the Royal Meteorological Society*, *127* (574), 1413-1432, 2001a.

Gray, L.J., S.J. Phipps, T.J. Dunkerton, M.P. Baldwin, E.F. Drysdale, and M.R. Allen, A data study of the influence of the equatorial upper stratosphere on northern-hemisphere stratospheric sudden warmings, *Quarterly Journal of the Royal Meteorological Society*, *127* (576), 1985-2003, 2001b.

Gray, L.J., and J.A. Pyle, A two-dimensional model of the quasi-biennial oscillation in ozone, *Journal of Atmospheric Sciences*, *46*, 203-220, 1989.

Hamilton, K., Effects of an imposed quasi biennial oscillation in a comprehensive troposphere stratosphere mesosphere general circulation model, *Journal of Atmospheric Sciences*, *55*, 2393-2418, 1998.

Hare, S.R., and N.J. Mantua, Empirical evidence for North Pacific regime shifts in 1977 and 1989, *Progress in Oceanography*, *47*, 103–145, 2000.

Haynes, P.H., The latitudinal structure of the quasi-biennial oscillation, *Quarterly Journal of the Royal Meteorological Society*, *124*, 2645-2670, 1998.

Holton, J.R., and J. Austin, The Influence of the Equatorial QBO on Sudden Stratospheric Warmings, *Journal of the Atmospheric Sciences*, *48* (4), 607-618, 1991.

Holton, J.R., and H.C. Tan, The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb, *Journal of Atmospheric Sciences*, *37*, 2200-2208, 1980.

Holton, J.R., and H.C. Tan, The quasi-biennial oscillation in the Northern Hemisphere lower stratosphere, *J. Meteor. Soc. Japan*, *60*, 140-148, 1982.

Hu, Y., and K.K. Tung, Tropospheric and equatorial influences on planetary-wave amplitude in the stratosphere, *Geophysical Research Letters*, *29*, 1019, doi:10.1029/2001GL013762, 2002.

Hu, Y., and K.K. Tung, Possible ozone-induced long-term changes in planetary wave activity in late winter, *Journal of Climate* (16), 3027-3038, 2003.

Huang, F.T., H.G. Mayr, C.A. Reber, J.M. Russell, M. Mlynczak, and J.G. Mengel, Stratospheric and mesospheric temperature variations for the quasi-biennial and semiannual (QBO and SAO) oscillations based on measurements from SABER (TIMED) and MLS (UARS), *Annales Geophysicae*, *24*, 2131–2149, 2006.

Kodera, K., and Y. Kuroda, Dynamical response to the solar cycle, *Journal of Geophysical Research-Atmospheres*, *107* (D24), art. no.-4749, 2002.

Labitzke, K., M. Kunze, and S. Bronnimann, Sunspots, the QBO and the stratosphere in the North Polar Region - 20 years later, *Meteorol. Zeitschrift*, *15*, 355-363, 2006.

Labitzke, K., and H. van Loon, Associations between the 11-year solar-cycle, the QBO and the atmosphere 1. The troposphere and stratosphere in the Northern Hemisphere in winter, *Journal of Atmospheric and Terrestrial Physics*, *50* (3), 197-206, 1988.

Manzini, E., M.A. Giorgetta, M. Esch, L. Kornblueh, and E. Roeckner, The influence of sea surface temperatures on the northern winter stratosphere: Ensemble simulations with the MAECHAM5 model, *Journal of Climate*, *19* (16), 3863-3881, 2006.

Matsuno, T., Vertical propagation of stationary planetary waves in the winter Northern Hemisphere, *Journal of Atmospheric Sciences*, *27*, 871-883, 1970.

Matsuno, T., A dynamical model of the stratospheric sudden warming, *Journal of Atmospheric Sciences*, *28*, 1479-1494, 1971.

McCormack, J.P., The influence of the 11-year solar cycle on the quasi-biennial oscillation, *Geophysical Research Letters*, *30* (22), art. no.-2162, 2003.

McIntyre, M.E., How well do we understand the dynamics of stratospheric warmings?, *J. Meteor. Soc. Japan*, *60*, 37-65, 1982.

Minobe, S., Interannual to interdecadal changes in the Bering Sea and concurrent 1998/99 changes over the North Pacific, *Progresses in Oceanograph*, *55*, 45-64, 2002.

Naito, Y., and I. Hirota, Interannual variability of the northern winter stratospheric circulation related to the QBO and the solar cycle, *Journal of Meteorological Society of Japan*, *75*, 925-937, 1997.

Naito, Y., M. Taguchi, and S. Yoden, A parameter sweep experiment on the effects of the equatorial QBO on stratospheric sudden warming events, *Journal of Atmospheric Sciences*, *60*, 1380-1394, 2003.

Nakamura, H., G. Lin, and T. Yamagata, Decadal climate variability in the North Pacific during the recent decades, *Bull. Am. Meteorol. Soc.*, *78*, 2215-2225, 1997.

Nathan, T.R., and E.C. Cordero, An ozone-modified refractive index for vertically propagating planetary waves, *Journal of Geophysical Research*, *112*, D02105, doi:10.1029/2006JD007357, 2007.

Naujokat, B., An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics., *Journal of Atmospheric Sciences*, *43*, 1873-1877, 1986.

Neumaier, A., and T. Schneider, Estimation of parameters and eigenmodes of multivariate autoregressive models, *ACM Transactions on Mathematical Software*, *27*, 27-57, 2001.

Nitta, T., and S. Yamada, Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation, *Journal of Meteorological Society ofJapan*, *67*, 375-383., 1989.

Pascoe, C.L., L.J. Gray, S.A. Crooks, M.N. Juckes, and M.P. Baldwin, The quasi-biennial oscillation: Analysis using ERA-40 data, *Journal of Geophysical Research-Atmospheres*, *110* (D8), D08105, doi:10.1029/2004JD004941, 2005.

Plumb, R.A., and R.C. Bell, A model of the quasi-biennial oscillation on an equatorial beta-plane, *Quarterly Journal of the Royal Meteorological Society*, *108*, 335-352, 1982.

Punge, H.J., and M.A. Giorgetta, Differences between the QBO in the first and in the second half of the ERA-40 reanalysis, *Atmospheric Chemistry and Physics*, *7*, 599-608, 2007.

Reed, R.J., The quasi-biennial oscillation of the atmosphere between 30 and 50 km over Ascension Island, *Journal of Atmospheric Sciences*, *22*, 331-333, 1965.

Rodionov, S.N., and J.E. Overland, Application of a sequential regime shift detection method to the Bering Sea ecosystem, *ICES J. Mar. Sci.*, *62*, 328-332, 2005.

Salby, M., and P. Callaghan, Connection between the solar cycle and the QBO: The missing link, *Journal of Climate*, *13* (14), 2652-2662, 2000.

Taguchi, M., and D.L. Hartmann, Increased occurrence of stratospheric sudden warmings during El Nino as simulated by WACCM, *Journal of Climate*, *19*, 324-332, 2006.

Tung, K.K., and R.S. Lindzen, Theory of stationary long waves. Part I: Simple theory of blocking, *Monthly Weather Review*, *107*, 714-734, 1979.

Uppala, S.M., et al., The ERA-40 reanalysis, *Quarterly Journal of the Royal Meteorological Society*, *131* (612), 2961-3012, 2005.

Wang, M., J.E. Overland, D.B. Percival, and H.O. Mofjeld, Change in the Arctic influence on Bering Sea climate during the twentieth century, *International Journal of Climatology*, *26* (4), 531-9, 2006.

Weatherhead, E.C., et al., Detecting the recovery of total column ozone, *Journal of Geophysical Research*, *105* (22,201– 22,210), 2000.

Yasuda, T., and K. Hanawa, Decadal changes in the mode waters in the midlatitude North Pacific, *Journal of Physical Oceanograph*, *27*, 858-870, 1997.

Figure Captions

Fig. 1. The QBO time series (*i.e.* de-seasonalized monthly mean zonal mean zonal wind at the equator) in m s^{-1} extracted from Era-40 and ECWMF operational on 11 pressure levels from 1958 to 2006. Red and blue colors represent westerly and easterly winds. The black solid lines are zero wind lines.

Fig. 2. e-QBO (left-hand panels) and w-QBO (right-hand panels) composites of the zonal mean zonal wind (lined contours) and temperature anomalies (color shaded contours) for November to January mean (top panels), and for February and March mean (bottom panels). Thick solid lines represent zero wind. The QBO phases, the calendar months, with the total number of data samples indicated on the top of each panel.

Fig. 3. Time series (black lines) of the extratropical zonal-mean (a) zonal wind at 54.4°N, 10 hPa and (b) and (c) temperature anomalies at 65.5°N, 50 hPa and at 65.5°N, 200 hPa, respectively, plotted against zonal-mean zonal wind at the equator at 50 hPa averaged over the extended winter period (November-March) (gray lines). The correlation coefficients and confidence levels (in brackets) for the entire period of 1958-2006 are given on the top of each sub-plot together with those for the sub-periods of 1958-1976, 1977-1997 and 1998-2006.

Fig. 4. Same as Fig. 3 but for late winter (February-March) averages.

Fig. 5. Running correlation coefficients between the equatorial QBO and the NH polar wind anomaly (first row) & temperature anomalies (second and third rows) with a 21-year window, using November to March mean (left-hand panels) and February to March mean (right-hand panels). The time series of the wind and temperature anomalies are the same as those shown in Figs. 3 and 4. The *p* values represent the levels of statistical significance in terms of the difference between the maximum and minimum values of the running correlation. See text for details.

Fig. 6. Composite differences between e-QBO and w-QBO for zonal-mean zonal wind anomalies (m s^{-1}), for the period of 1958-2006, 1958-1976 and 1977-1997 respectively for

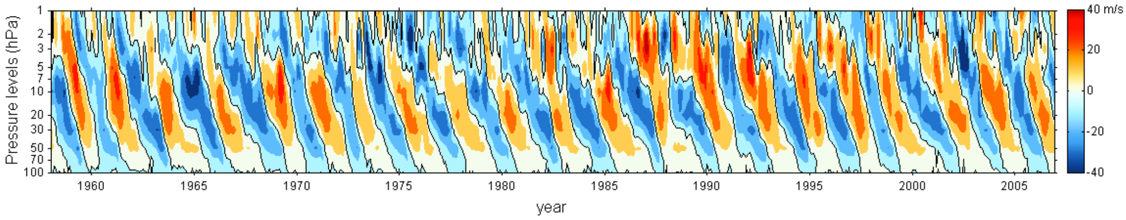
each of the months from October to April. The data have been first de-seasonalized using monthly mean data from 1958-2006, grouped into e-QBO, and w-QBO. The differences of the calculated mean values for each group are described in the text. The areas enclosed within the grey lines indicate that the differences are statistically significance from zero with a confidence level of 95% or above, calculated using a Monte Carlo trial based non-parametric test.

Fig. 7. Same as Fig. 6 but for the temperature anomalies.

Fig. 8. Major SSWs occurrence grouped by early, middle, late and extended winter and the phases of the QBO, for the periods of 1958-2006, 1958-1976, 1977-1997, and 1998-2006 (from left to right). Westerly and easterly QBO are defined as >/< 0, respectively.

Fig. 9. Linear correlations between Jan-Feb mean QBO and Jan-Feb mean-zonal mean zonal wind anomalies (1st row), and temperature anomalies (2nd row), under all solar conditions (1st column), when Dec-Feb mean F10.7 solar radio flux F_s is high (2nd column), and when F_s is low (3rd column). High/low F10.7 is defined as the standardized F_s >/< than +/– 0.2. Contour interval is ±0.1correlation coefficient and the thick black contour is zero correlation. The light and dark shaded areas indicate that the differences are statistically significance from zero with a confidence level of 90% and 95% or above, respectively.

1



Pressure levels (hPa)
1
2
3
5
7
10
20
30
50
70
100
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
year
40 m/s
20
0
-20
-40

Fig. 1

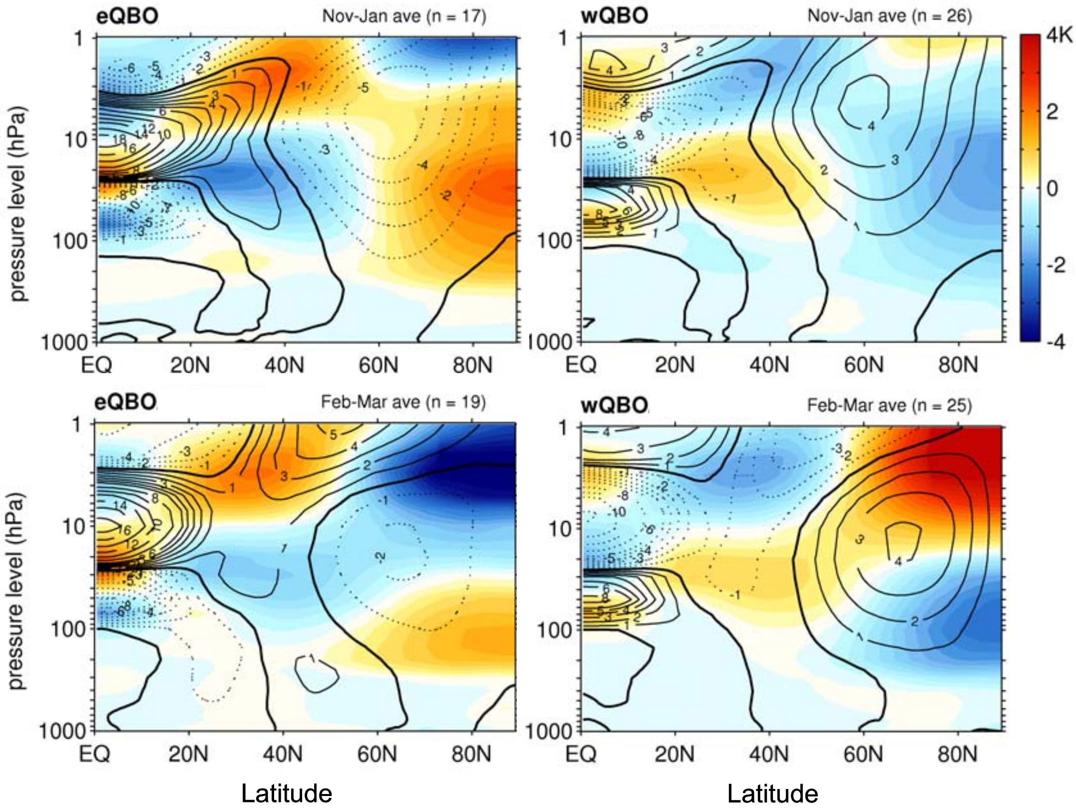

eQBO
Nov-Jan ave (n = 17)
wQBO
Nov-Jan ave (n = 26)
eQBO
Feb-Mar ave (n = 19)
wQBO
Feb-Mar ave (n = 25)
pressure level (hPa)
Latitude
EQ
20N
40N
60N
80N
4K
2
0
-2
-4

Fig. 2

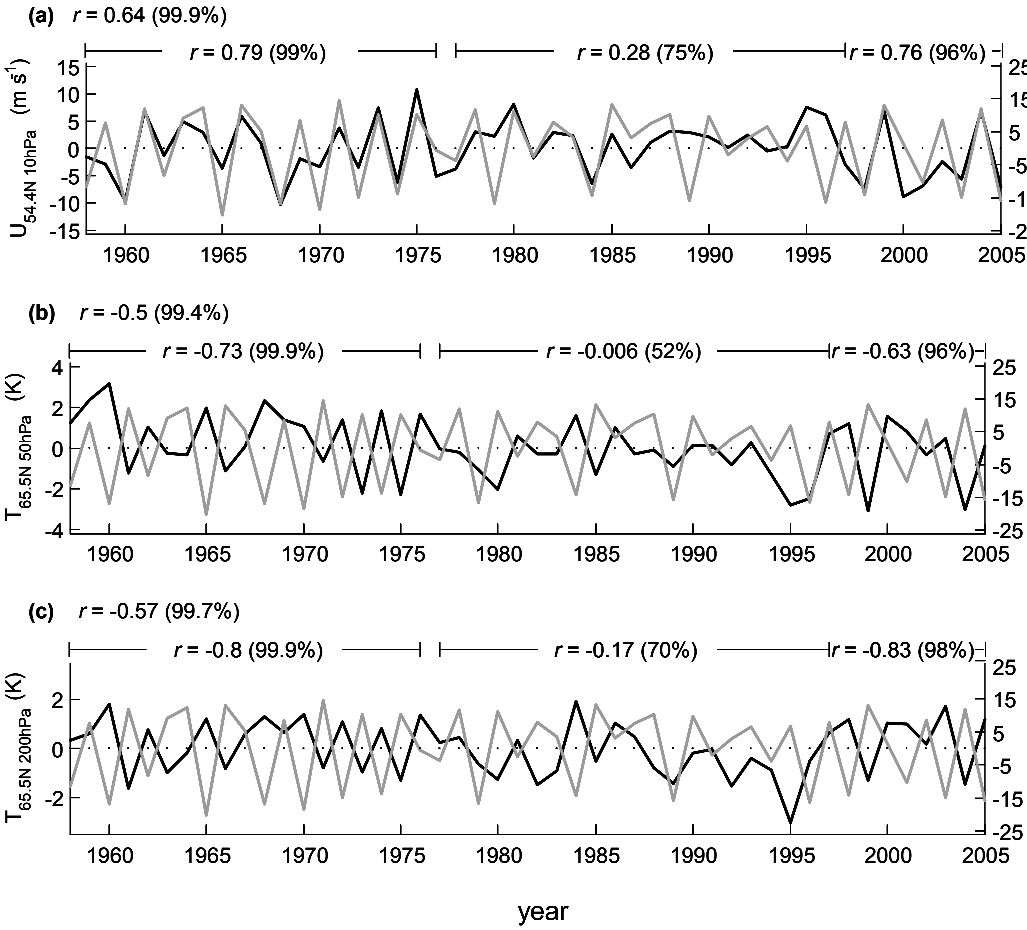

(a) r = 0.64 (99.9%)
r = 0.79 (99%)
r = 0.28 (75%)
r = 0.76 (96%)
U54.4N 10hPa (m s-1)
UEQ 50hPa (m s-1)
(b) r = -0.5 (99.4%)
r = -0.73 (99.9%)
r = -0.006 (52%)
r = -0.63 (96%)
T65.5N 50hPa (K)
Ueq 50hPa (m s-1)
(c) r = -0.57 (99.7%)
r = -0.8 (99.9%)
r = -0.17 (70%)
r = -0.83 (98%)
T65.5N 200hPa (K)
Ueq 50hPa (m s-1)
year

Fig. 3

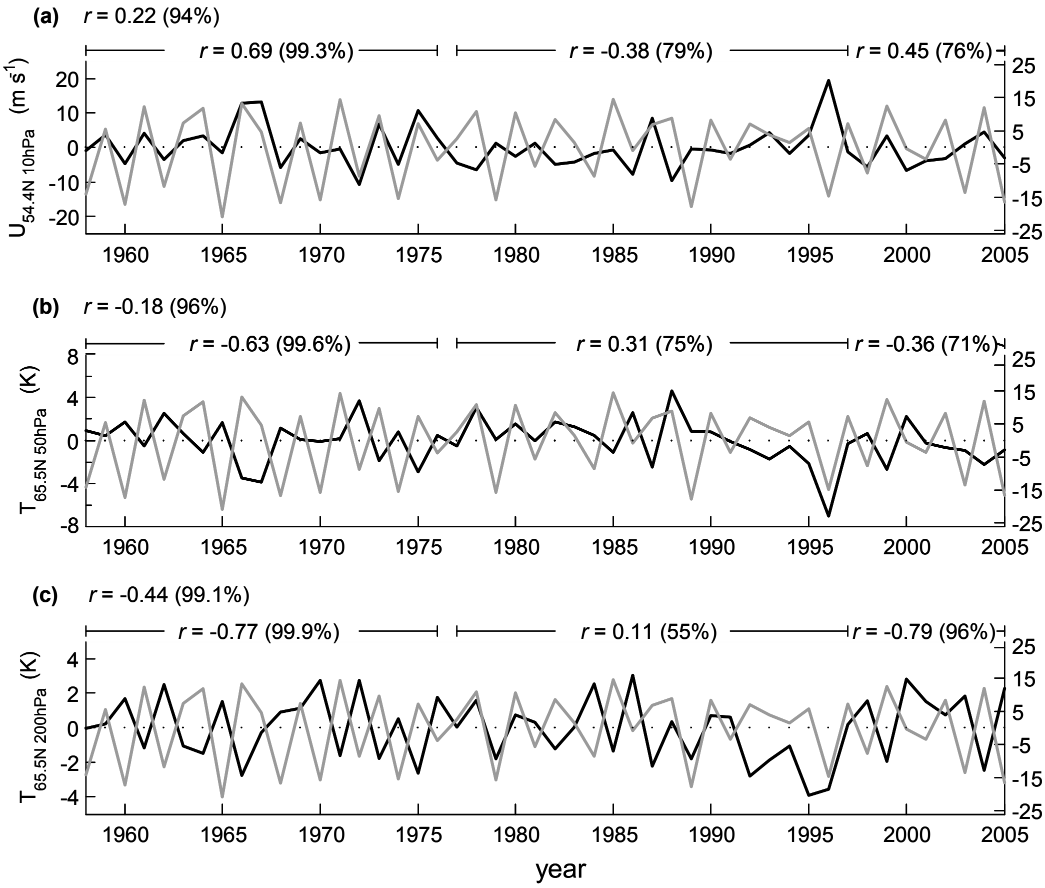

(a) r = 0.22 (94%)
r = 0.69 (99.3%)
r = -0.38 (79%)
r = 0.45 (76%)
U54.4N 10hPa (m s-1)
Ueq 50hPa (m s-1)
(b) r = -0.18 (96%)
r = -0.63 (99.6%)
r = 0.31 (75%)
r = -0.36 (71%)
T65.5N 50hPa (K)
Ueq 50hPa (m s-1)
(c) r = -0.44 (99.1%)
r = -0.77 (99.9%)
r = 0.11 (55%)
r = -0.79 (96%)
T65.5N 200hPa (K)
Ueq 50hPa (m s-1)
year

Fig. 4

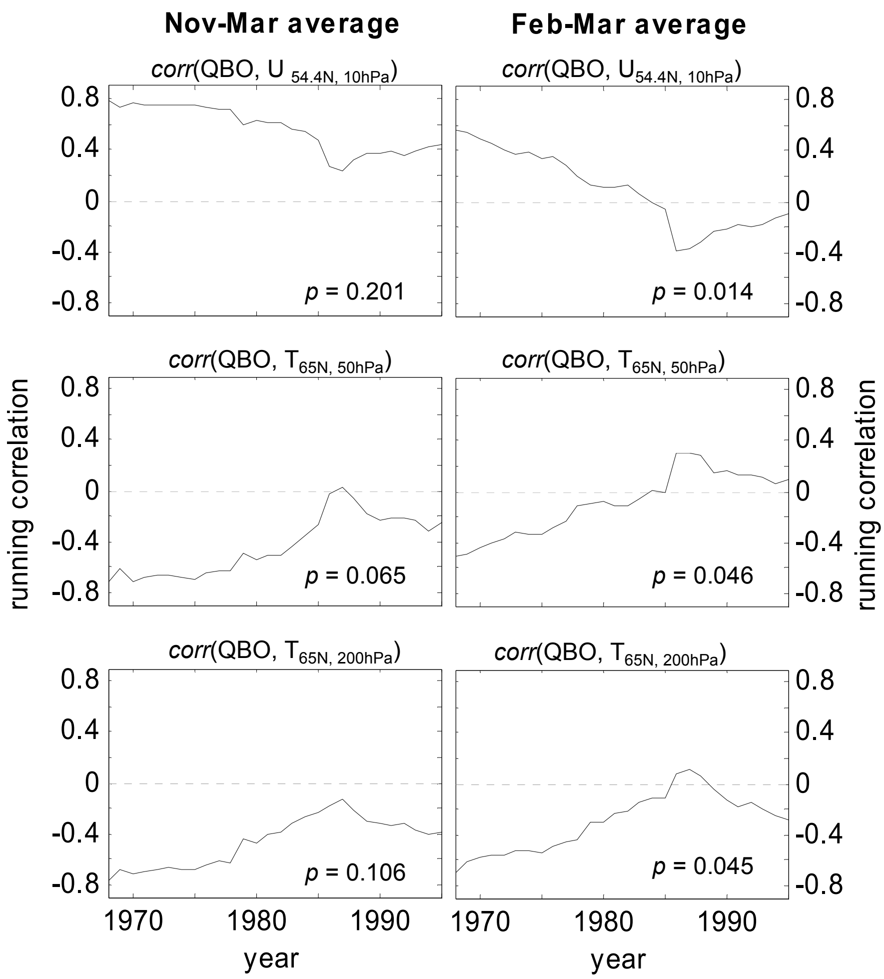
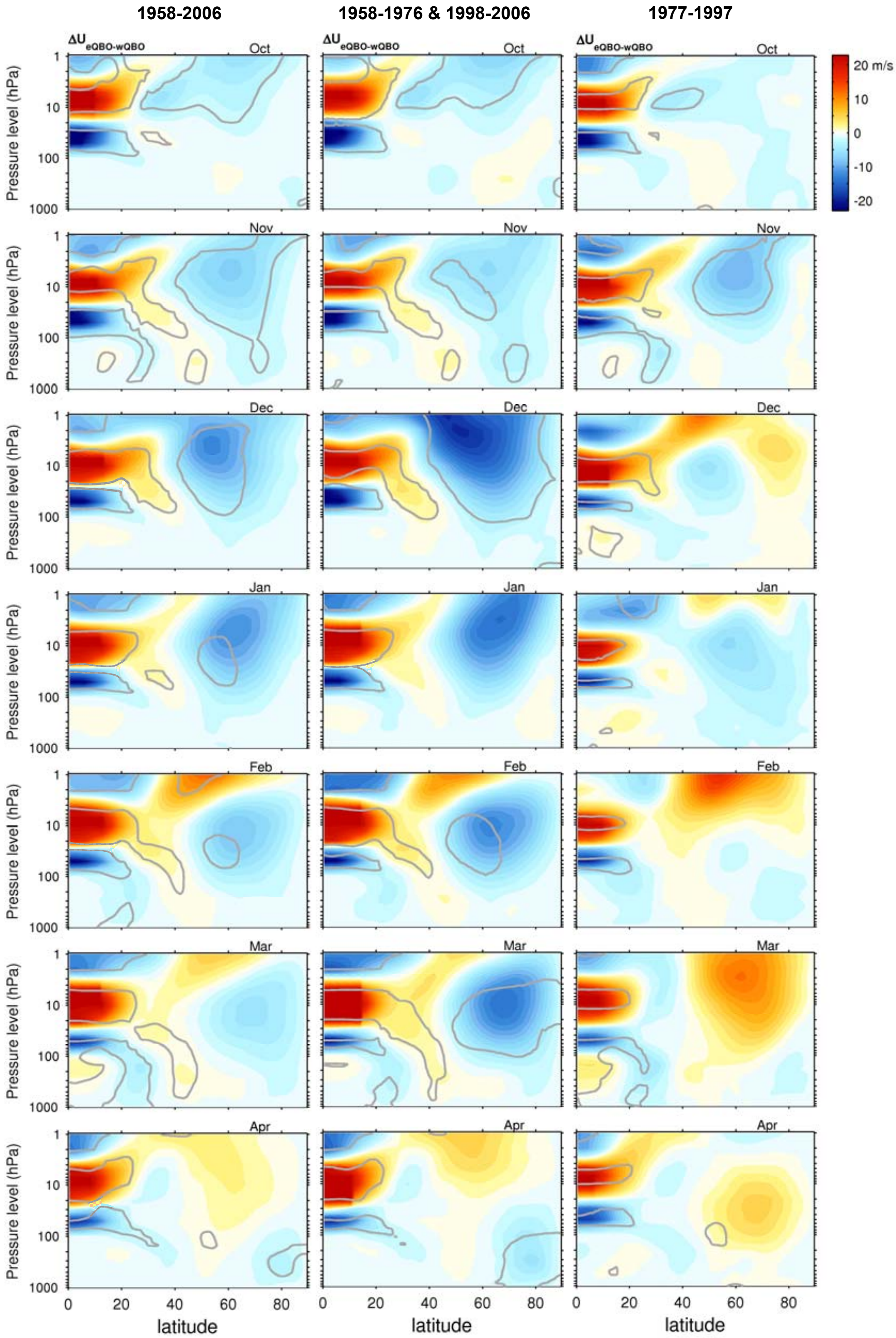
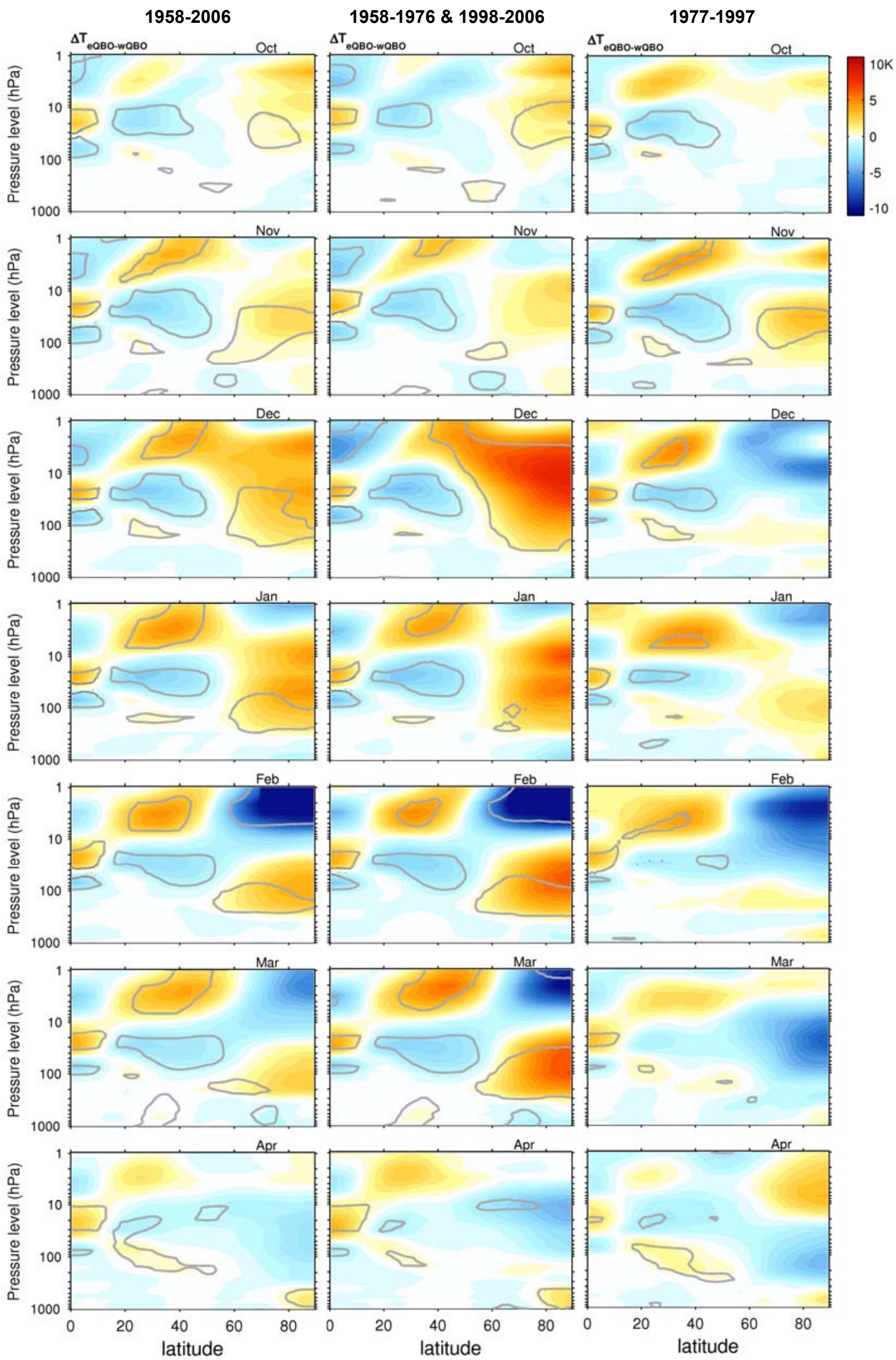

Nov-Mar average
Feb-Mar average
corr(QBO, U 54.4N, 10hPa)
corr(QBO, U54.4N, 10hPa)
p = 0.201
p = 0.014
corr(QBO, T65N, 50hPa)
corr(QBO, T65N, 50hPa)
p = 0.065
p = 0.046
corr(QBO, T65N, 200hPa)
corr(QBO, T65N, 200hPa)
p = 0.106
p = 0.045
running correlation
running correlation
0.8
0.4
0
-0.4
-0.8
1970
1980
1990
year
year

Fig. 5


1958-2006
1958-1976 & 1998-2006
1977-1997
ΔU eQBO-wQBO
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Pressure level (hPa)
1
10
100
1000
20 m/s
10
0
-10
-20
0
20
40
60
80
latitude

1

Fig. 6


1958-2006
1958-1976 & 1998-2006
1977-1997
$\Delta T_{eQBO-wQBO}$
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Pressure level (hPa)
latitude
10K
5
0
-5
-10

1 **Fig. 7**

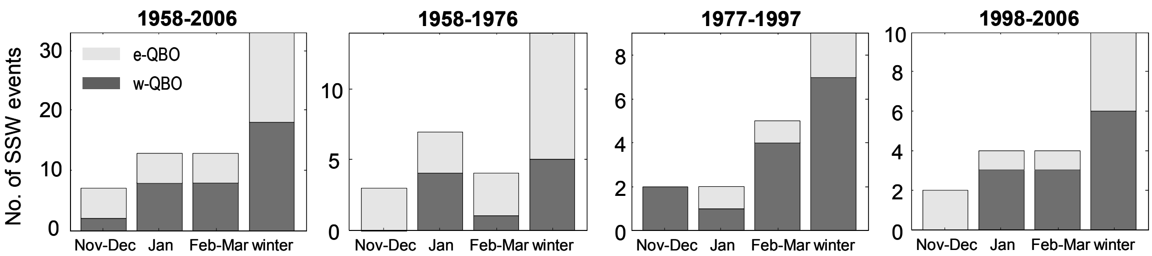
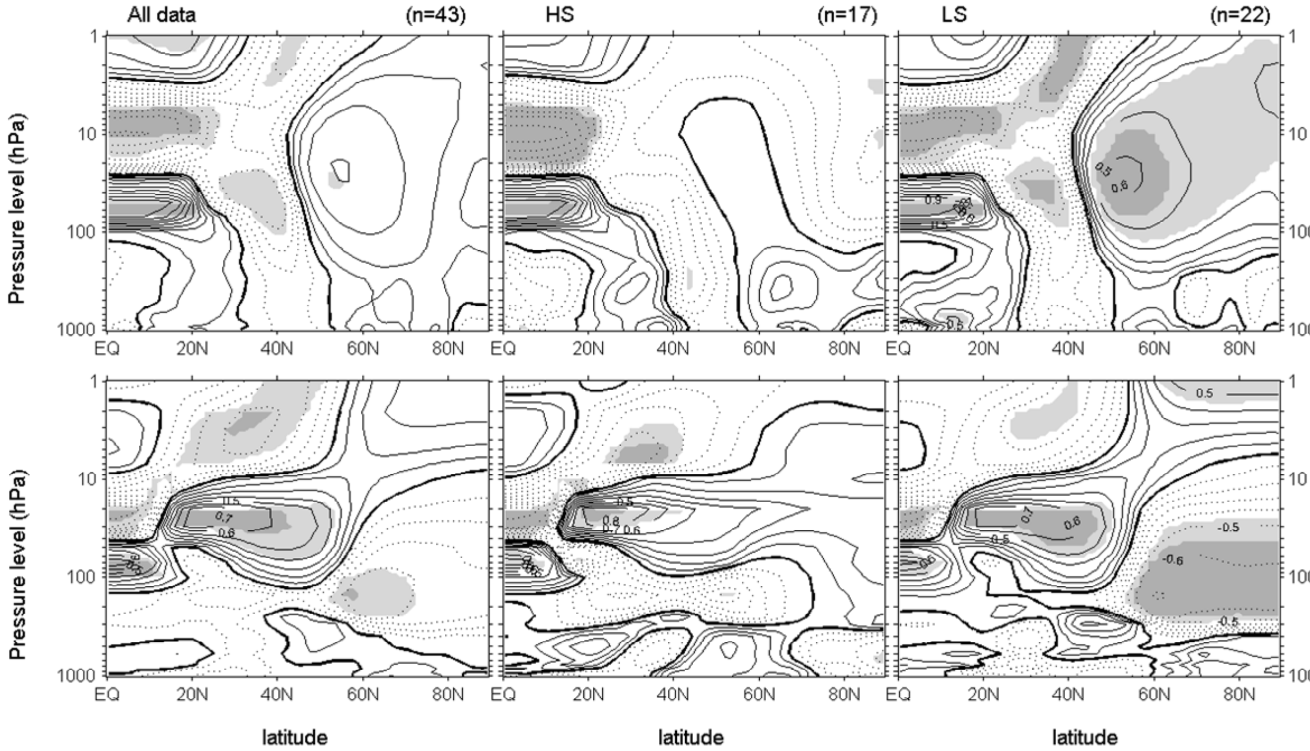

1958-2006
1958-1976
1977-1997
1998-2006
e-QBO
w-QBO
No. of SSW events
Nov-Dec
Jan
Feb-Mar
winter

Fig. 8



All data
(n=43)
HS
(n=17)
LS
(n=22)
Pressure level (hPa)
latitude
EQ
20N
40N
60N
80N
1
10
100
1000

1

Fig. 9