

Life cycle of the QBO-modulated 11-year solar cycle signals in the Northern Hemispheric winter

Hua Lu,^{a,*} Lesley J. Gray,^b Mark P. Baldwin^c and Martin J. Jarvis^a

^aPhysical Sciences Division, British Antarctic Survey, Cambridge, UK

^bNCAS-Climate, Meteorology Department, Reading University, Reading, UK

^cNorthwest Research Associates, Redmond, Washington, USA

ABSTRACT: This paper provides some insights on the quasi-biennial oscillation (QBO) modulated 11-year solar cycle (11-yr SC) signals in Northern Hemisphere (NH) winter temperature and zonal wind. Daily ERA-40 Reanalysis and ECMWF Operational data for the period of 1958–2006 were used to examine the seasonal evolution of the QBO-solar cycle relationship at various pressure levels up to the stratopause. The results show that the solar signals in the NH winter extratropics are indeed QBO-phase dependent, moving poleward and downward as winter progresses with a faster descent rate under westerly QBO than under easterly QBO. In the stratosphere, the signals are highly significant in late January to early March and have a life span of ~30–50 days. Under westerly QBO, the stratospheric solar signals clearly lead and connect to those in the troposphere in late March and early April where they have a life span of ~10 days. As the structure changes considerably from the upper stratosphere to the lower troposphere, the exact month when the maximum solar signals occur depends largely on the altitude chosen.

For the low-latitude stratosphere, our analysis supports a vertical double-peaked structure of positive signature of the 11-yr SC in temperature, and demonstrates that this structure is further modulated by the QBO. These solar signals have a longer life span (~3–4 months) in comparison to those in the extratropics. The solar signals in the lower stratosphere are stronger in early winter but weaker in late winter, while the reverse holds in the upper stratosphere. Copyright © 2009 Royal Meteorological Society

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1. Introduction

Studies have shown that the Northern Hemisphere (NH) winter temperature and circulation may be influenced by both the quasi-biennial oscillation (QBO) of the equatorial lower stratosphere (Holton and Tan, 1980; Naito *et al.*, 2003) and the 11-year solar cycle (11-yr SC) (Labitzke, 1987; Labitzke and van Loon, 1988; Kodera and Kuroda, 2002). It has been shown that, on average, when the equatorial winds near 50 hPa are easterly, the NH polar winter in the lower stratosphere tends to be warmer and the polar vortex becomes more disturbed, and vice versa when the equatorial winds are westerly (Holton and Tan, 1980; 1982; Naito *et al.*, 2003; Lu *et al.*, 2008).

However, Labitzke (1987) suggested a more complicated, nonlinear interaction between the QBO and the 11-yr SC, and found that the north polar temperature at 30 hPa is positively correlated with the 11-yr SC when the QBO is westerly (wQBO), and negatively correlated when the QBO is easterly (eQBO). Thus, at solar maximum, the QBO perturbation on the NH polar vortex appears to be opposite to the Holton and Tan (HT)

relationship. Using a 30-year (1956–1986) stratospheric dataset of the Freie Universität Berlin (FUB), Labitzke and van Loon (1988) expanded the work of Labitzke (1987) and found that similar correlations exist between the 11-yr solar cycle and January/February averaged polar temperature and geopotential heights at 30 hPa. They found that Sudden Stratospheric Warmings (SSWs) are more prevalent in low solar (LS) years during the eQBO phase and in high solar (HS) years during the wQBO phase, suggesting that the HT relationship is reversed during HS years. Naito and Hirota (1997) updated their study using a 37-year (1958–1994) stratospheric temperature dataset of FUB combined with a 31-year (1963–1994) National Meteorological Centre (NMC) global zonal-mean zonal wind dataset and confirmed that the ‘reversed’ behaviour found by Labitzke and van Loon (1988) held over this extended period. Gray *et al.* (2001) examined radiosonde equatorial winds and polar temperature data for 1955–1999 and found a negative correlation between lower stratospheric equatorial winds and NH polar stratospheric temperature, indicating a strong HT relationship only during LS years, and a very weak positive correlation during HS years. They consequently suggested that the HT relationship is weakened during solar maximum but not necessarily reversed.

*Correspondence to: Hua Lu, Physical Sciences Division, British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK. E-mail: hlu@bas.ac.uk

This QBO-SC relationship has been re-examined and confirmed more recently by several authors using reanalysis data (Labitzke and van Loon, 2000; Labitzke, 2001, 2004, 2005; Salby and Callaghan, 2006). Labitzke *et al.* (2006) (hereafter LKB2006) used the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from 1958 to 2006 combined with earlier data from statistical reconstructions based on historical upper air data, thus extending the data period to 65 years (1942–2006). This new analysis, which concentrated on February in the NH winter and July in the Southern Hemisphere (SH) winter, confirmed their earlier results.

Studies have shown that variations in 11-year solar irradiance and subsequent ultraviolet (UV) absorption by ozone cause changes in temperature and wind in the upper stratosphere (Hood, 2004; Crooks and Gray, 2005). These relatively weak direct changes could alter the upward propagation of planetary-scale waves, and lead to an indirect feedback on the lower atmosphere through a modulation of the polar-night jet as well as through a change of the stratospheric mean circulation – Brewer-Dobson (BD) circulation (Kodera and Kuroda, 2002). The change in BD circulation may also influence the transport of ozone to the lower stratosphere (Hood, 2004), which will also cause temperature and wind variations in the lower stratosphere due to diabatic heating (e.g. Gray *et al.*, 2009). Finally, a direct modulation of the equatorial QBO descent rates by the SC has been proposed (McCormack, 2003; Pascoe *et al.*, 2005; McCormack *et al.*, 2007). However, it is not clear which of these, if any, is the dominant mechanism for QBO-SC interaction.

The mechanism by which the QBO modulates the solar responses in the polar stratosphere during the NH winter is still not understood. More specifically, it is not clear why the QBO-SC influence on NH extratropical circulation and SSWs appears to be strong primarily in February (LKB2006). The main purpose of this paper is to further examine the QBO-SC relationship over the whole of the NH winter, with a strong emphasis on its intraseasonal life cycle and the interaction between the equatorial and polar regions. To study when and where the solar signals are initialized, strengthened, and finally weakened, the five winter months from November to March are examined using monthly and sub-monthly averages of temperature and zonal wind. We examine whether the relationship holds coherently over several months, whether the relationship is statistically significant and how the solar signals move in altitude and latitude through the winter.

2. Data and methods

The data used are daily mean zonal winds and temperatures from the 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). Both datasets extend to 1 hPa (~50 km), thus allowing

an examination of the solar signals throughout the stratosphere. The daily data have not previously been used for this purpose and this work is therefore complementary to earlier analyses (e.g. LKB2006; Gray *et al.*, 2004) by providing more-detailed temporal information of the QBO-SC relationship. The ERA-40 Reanalysis has a spectral resolution of T159, corresponding to a 1.125° horizontal resolution in latitude and longitude. The data are available at 23 standard pressure surfaces from 1000 hPa to 1 hPa, which were assimilated using direct radiosonde and satellite measurements (Uppala *et al.*, 2005). The ECMWF Operational data were output from the ongoing analyses produced by the most recent ECMWF Integrated Forecasting System (IFS) model. Data from September 2002 to the present day are available on the same 1.125° grid and on 21 pressure levels, which are identical to the ERA-40 data except without the 600 and 775 hPa levels. For consistency, only the data for those 21 pressure levels are used here.

The QBO was defined using the deseasonalized zonal wind from the blended ERA-40 and Operational data at 0.56°N , 50 hPa to be consistent with previous work (Holton and Tan, 1980; Labitzke and van Loon, 1988). The phase of the QBO was determined for each specific period after an averaging window was applied to both the QBO and the atmospheric variable it correlates to. Transition periods when the absolute values of the QBO were smaller than 2 m s^{-1} were excluded from the analysis. Qualitatively similar results were obtained if the phase of the QBO is defined only for those winters for which the same phase of the QBO remains throughout. Slightly weaker but oppositely-signed solar signals are obtainable if the deseasonalized zonal wind at 5 hPa is used to define the QBO phase. Qualitatively similar results can also be obtained if the QBO phase is defined by zonal wind measurements from equatorial radiosondes at 40–50 hPa. However, much weaker correlations are found when other QBO levels were used.

Possible contamination by the temporary heating caused by volcanic aerosols in the stratosphere was examined by excluding or including two years of data following three major eruptions (i.e. Agung in March 1963, El Chichón in March 1982, and Pinatubo in June 1991). Qualitatively similar results were obtained for the spatial pattern and significances of the solar signals in either case. In the results reported below, all winter data are included, to be consistent with LKB2006.

Following previous studies, 10.7 cm solar radio fluxes (in units of $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$) are used as a proxy for the 11-yr SC. Daily observed 10.7 cm solar radio fluxes were obtained from the National Geophysical Data Center (NGDC) website (www.ngdc.noaa.gov/stp). Most previous studies have used 1-month to 2-month averaged 10.7 cm solar radio fluxes. We tested and examined 1-month through to 12-month averaged 10.7 cm solar radio fluxes preceding the day when the atmospheric variable averages were taken, and only found ~10% of variation in correlation coefficients and an even smaller amount of change in spatial coverage of the solar signals. This suggests that the signals reported in this paper are

mostly due to low-frequency variations (i.e. the 11-yr cycle) in solar inputs. Although qualitatively similar results are obtained using any averaging period from 1 month to 12 months, we have employed 6-month averaged 10.7 cm solar radio fluxes (F_s hereafter) since this gives the most consistent results with the highest overall correlation coefficients and statistical confidence levels. More specifically, all the solar signals reported below were results from using 6-month averaged 10.7 cm solar radio fluxes preceding the day when the atmospheric variable averages were taken.

The main diagnostic tools employed are linear correlation and composite analysis. The statistical confidence levels of the correlations are calculated using the standard Student t -test. The same Monte-Carlo significance test used by Lu *et al.* (2007) is used to test the statistical significance of the composite differences.

3. Results

3.1. Solar signals in the NH polar region

In agreement with previous studies (e.g. LKB2006), no significant correlation between F_s and atmospheric temperatures from November through January was found in the NH polar region when monthly-averaged temperatures were employed, but significant solar signals are found in February and March. Figure 1 shows the latitude–height cross-section of the correlation between 6-month averaged F10.7 cm solar radio fluxes (F_s) and monthly mean temperature in the NH for February and March, for the period 1958 to 2006. In the NH polar stratosphere, rather weak positive solar signals with maximum correlation coefficient $r_{\max} = 0.3$ emerge only in February when all years are used (upper-left panel), while significantly stronger signals appear in the NH polar region when the data are separated into wQBO and eQBO (middle and right-hand columns). In February, a large area of the Arctic lower stratosphere (57° – 90° N, 20–300 hPa) exhibits significant positive correlations under wQBO, while significant negative correlations are found at the lowermost stratosphere (70° – 90° N, 100–300 hPa) under eQBO. For both the QBO phases, oppositely-signed solar signals to those in the Arctic lower stratosphere are found in the Arctic upper stratosphere, though the signals associated with wQBO appear at a higher altitude than those associated with eQBO. In March, positive correlations are found (60° – 80° N, 100–200 hPa) and negative correlations occur at around 70° – 90° N, 10 hPa under wQBO. Weak negative correlations are found at around 70° – 90° N, 150–200 hPa, and significant positive correlations are found at around 40° – 60° N, 30–100 hPa under eQBO. Comparing to those in February, the correlation patterns in March imply possible descent of the solar signals.

The solar signals in February temperature compare exceedingly well with LKB2006. The deep positive solar signals in the polar stratosphere under wQBO at 10–250 hPa have a maximum correlation coefficient of

$r_{\max} = 0.82$ in this study compared with $r_{\max} = 0.6$ in LKB2006. This is partially due to the fact that we use 6-month averaged F_s while LKB2006 used monthly mean F_s . It may also be partially due to the use of less reliable data pre-1958 by LKB2006. The dipolar structure shown here over the pole under eQBO is again similar to that in LKB2006, who, because they used data extending vertically only up to 10 hPa, were only able to show a hint of the positive correlation above ~ 20 hPa. In the current study this region of positive correlation reaches its maximum correlation coefficient of 0.65 near 5 hPa.

To show the temporal evolution of the solar signals, Figure 2 plots the time series of deseasonalized February temperatures T_{Feb} against F_s Aug–Jan at 85° N, 50 hPa in the wQBO phase, and at 85° N, 200 hPa in the eQBO phase. These locations represent maximum and minimum correlation coefficients in the lower stratosphere under wQBO and eQBO respectively in February (see Figure 1). It shows that the positive correlation under wQBO attains $r = 0.82$ with a confidence level of 99.9%. Similarly, the negative correlation under eQBO has $r = -0.63$ with a confidence level of 99.3%. There are very few eQBO years in the 1990s, resulting in fewer data points around this period. Winter 1999/2000 under wQBO and 1971/1972, 1974/1975, 1996/1997, 2001/2002 winters under eQBO appear to be anomalous for the correlations. The results agree qualitatively with Labitzke and van Loon (1988) and Gray *et al.* (2001), who used January–February averaged temperatures at ~ 30 hPa (24 km) at the North Pole and January–February mean F10.7 cm solar radio fluxes.

Figure 3 shows the correlation between F_s and monthly-mean zonal-mean zonal wind in February and March. A similar dependence on the QBO phase is also evident. When all years are used, weak negative solar signals ($r_{\max} = 0.4$, confidence levels $\geq 95\%$) appear in the Arctic upper stratosphere in February, while no significant correlation can be found in March. Similar to the solar signals in the temperature, clearer and much stronger solar signals appear when the data are separated into wQBO and eQBO. In February and under wQBO, the entire stratospheric extratropics are covered by negative correlations ($r_{\max} = 0.7$, confidence levels $\geq 95\%$), indicating that the stratospheric polar vortex is more disturbed at HS and more stable at LS. Under eQBO, positive signals are found in the Arctic lower stratosphere and around 55° – 70° N in the troposphere while negative signals appear at midlatitudes extending from the surface to the upper stratosphere. From February to March, the high-latitude negative correlations in wQBO years descend from around 1–100 hPa to 30–1000 hPa, and the centre of the positive correlations in eQBO years move poleward and downward from around 10–200 hPa and 60° N to 100–1000 hPa and 75° N.

Similar to Figure 2, Figure 4 plots the time series of deseasonalized February zonal wind U_{Feb} against F_s Jul–Jan at 70° N, 10 hPa in the wQBO phase and at 70° N, 100 hPa in the eQBO phase. Those locations represent minimum and maximum correlation coefficients in February under wQBO and eQBO respectively (see

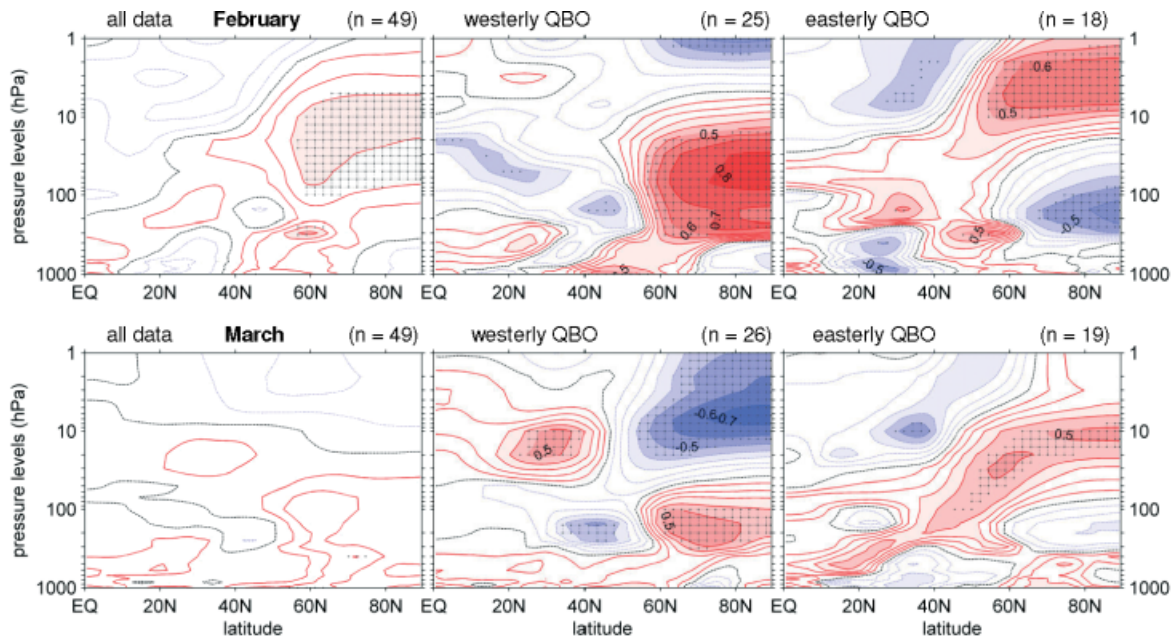


Figure 1. Latitude–height cross-section of correlations between monthly-averaged zonal mean temperature and 6-month averaged F10.7 cm solar flux (F_s with units of $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$) preceding the temperature averages for all years (the 1st column), under wQBO (the 2nd column), and under eQBO (the 3rd column). Top row: February, bottom row: March. The number of data points (i.e. years) used to calculate the correlation coefficients (r) are indicated on the top of each panel. Red solid, blue dotted and black dotted lines are positive, negative and zero correlations, respectively. The contour interval is ± 0.1 . Shaded areas denote confidence levels above 95%, calculated using standard one-sided t -test.

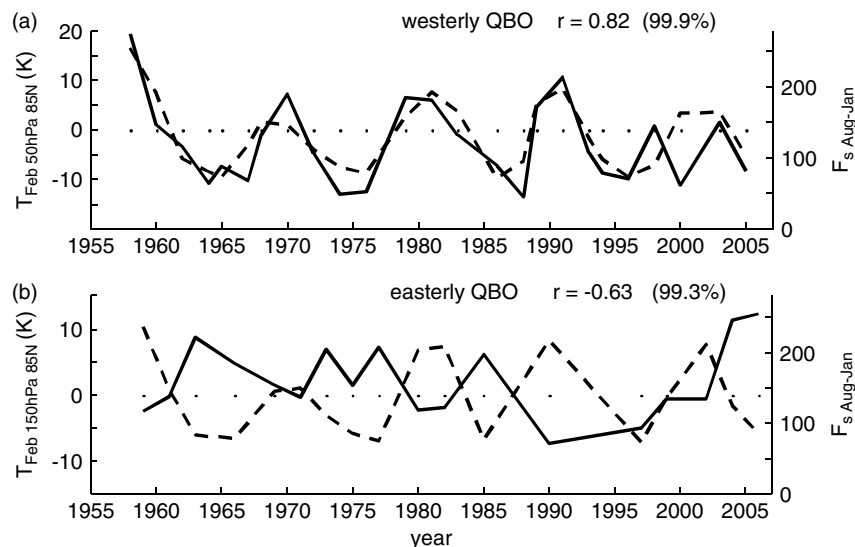


Figure 2. Time series of the 6-month averaged F10.7 cm solar flux (F_s , the dashed line) and the deseasonalized February temperature at 85°N, (a) at 50 hPa under wQBO (the solid line) and (b) at 150 hPa under eQBO (the solid line). The correlation coefficients and statistical confidence levels (in brackets) are shown in the top of each panel.

Figure 3). Under wQBO, the correlation is -0.78 , significant at the 99.9% confidence level. Under eQBO, the correlation is 0.65 , significant at the 99.1% confidence level. Similar to Figure 2, 1999/2000 winter under wQBO and 1974/1975, 1996/1997, 2001/2002 winters under eQBO appear to be anomalous.

Further sensitivity studies using data from different time periods gave qualitatively similar results for those QBO-modulated solar signals in the high latitudes shown in Figures 1 and 3. Including or excluding the years affected by volcanic eruptions also makes little change

to the general features of the signals. In addition, linear de-trending or removing the lower frequency components does not alter the general spatial patterns and confidence levels. This agrees well with Salby and Callaghan (2006) who also found that the QBO-SC relationship during February primarily exists in the high-frequency component of the temperature.

The fact that the time series of the El Niño/Southern Oscillation (ENSO) and F10.7 cm solar flux F_s are only weakly correlated helps to rule out a linear contamination of the QBO-SC relationship by ENSO. However, it does

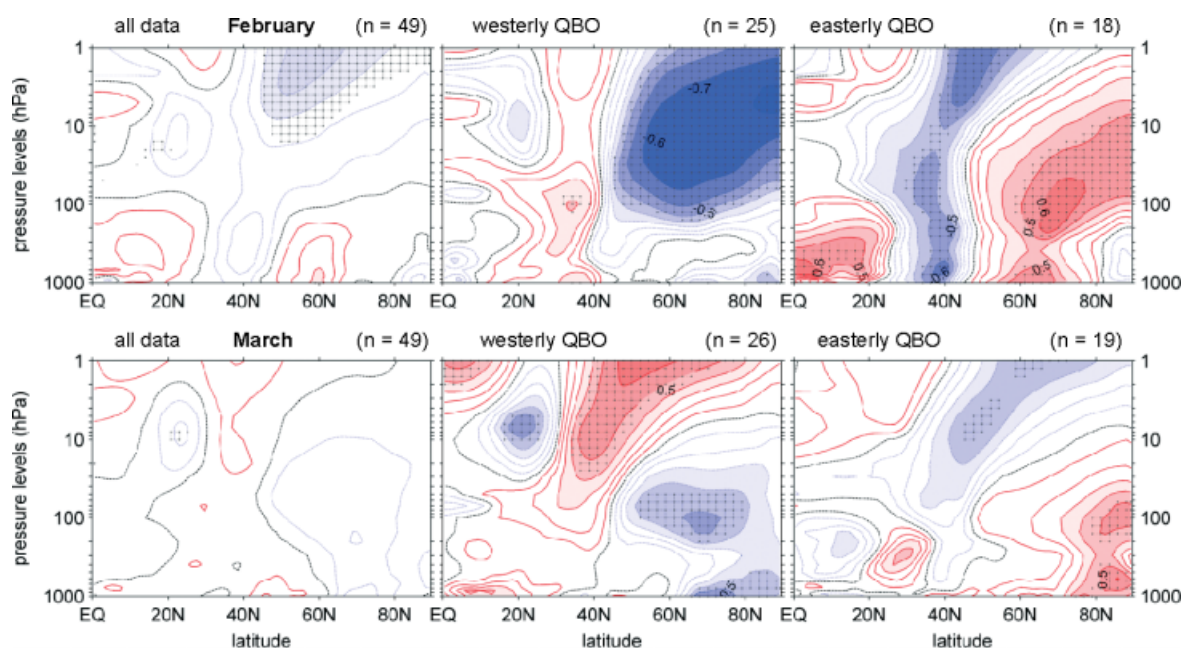


Figure 3. Same as Figure 1 but the temperatures are replaced by the zonal winds.

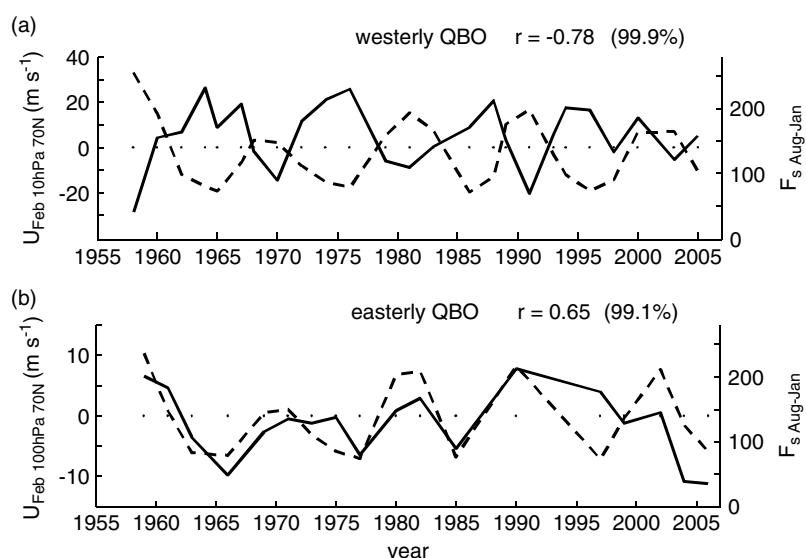


Figure 4. Same as Figure 2 but for the deseasonalized zonal-mean zonal wind (a) at 70°N, 10 hPa under wQBO, and (b) at 70°N, 100 hPa under eQBO.

not rule out the possibility that ENSO might modulate the QBO-SC relationship through nonlinear processes. It is interesting to note that all the anomalous winters shown in Figures 3 and 4 happened to be when ENSO was in its deep La Niña phase, identified as those winters for which the December–February NINO3.4 exceeds 0.5 of its standard deviations (see <http://cses.washington.edu/cig/pnwc/compensopdo.shtml>). Camp and Tung (2007) found that, during December–February, zonal mean temperature in the polar stratosphere at 10–50 hPa was 4 K warmer in the El Niño years than in the La Niña years, while no significant ENSO signals were detectable at low latitudes. By using two different general-circulation models (GCMs), García-Herrera *et al.* (2006) showed that the ENSO signature in zonal mean

temperature in the Arctic stratosphere was characterized by a gradually descending dipole pattern with a negative cell in the upper stratosphere and positive cell in the mid to lower stratosphere, and it is most significant in the NH winter. They showed that vertical wave propagation and divergence of Eliassen-Palm flux were noticeably enhanced in midlatitudes of the NH during El Niño winters, and the enhanced wave driving forced a stronger BD-circulation in the stratosphere and caused cooling in the tropical lower stratosphere and warming at higher latitudes. Comparing Figure 1 to Fig. 13 of García-Herrera *et al.* (2006), the pattern of ENSO signature derived from the GCMs is quite similar to the solar signals under wQBO, while the ENSO signature derived from ERA-40 data shows a vertically reversed pattern similar

to the solar signals under eQBO. The ENSO signature shown by García-Herrera *et al.* (2006) was based on data in 1979–1999 when the ENSO was anomalously more positive. It is therefore hard to tell how ENSO might affect longer-term variation of the QBO-SC relationship, as the stratosphere polar vortex responses to the QBO, solar and ENSO involve nonlinear interaction between zonal wind and wave forcing and their further impact on the residual circulation (Holton and Tan, 1980; 1982; Kodera and Kuroda, 2002; García-Herrera *et al.*, 2006).

For fixed latitudes with a higher temporal resolution, Figure 5 shows running correlations between F_s and an 11-day averaged temperature at 90°N (upper panels), and zonal-mean zonal wind anomaly at 80°N (lower panels), under wQBO (left-hand panels) and eQBO (right-hand panels). The correlations are plotted at the 6th day of the 11-day averages and all available data since 1958 are used. It shows that, under wQBO, the positive solar signals in the polar temperature descend from 10 hPa to 300 hPa from late January to mid-March while the negative signals descend from 1 hPa to 30 hPa from mid-February to early April. Under eQBO, a similar downward propagating behaviour is seen in the temperature correlations, except that the correlations are approximately opposite in sign to those under wQBO and appear to have a slower descent rate. The wind correlations follow the pattern of the temperature correlations. Under wQBO, the solar signals

in the polar zonal-mean zonal wind are characterized by a downward descent of negative correlations from 1 hPa to the surface and from mid-January to mid-March, while under eQBO, they are characterized by positive correlations from 10 hPa to 100 hPa and from early February to early March. The tropospheric signals under eQBO emerge in late March and appear to be disconnected from those from the stratosphere. Note that qualitatively similar correlation patterns can be obtained by selecting any latitude from 70°N to 90°N and using any running window in the range from 7 days to 40 days. Similar results can also be obtained if only the data since September 1978 are used. The solar signals in the NH polar stratosphere are found to have a life span of ~30–50 days, which is similar to the thermal relaxation time-scale in the lower stratosphere (Newman and Rosenfield, 1997). In the troposphere, the life span of solar signals is about 10 days.

From Figure 5, it is immediately evident why such a large signal is seen in the monthly-averaged analysis in February/March under wQBO, due to the timing of the anomaly across the monthly boundaries. In the wQBO phase, the positive temperature correlations (top left panel) appears almost simultaneously at all heights from 1 hPa down to ~300 hPa through late January. This is consistent with a higher frequency of SSWs in HS wQBO years (Labitzke and van Loon, 1988; LKB2006). SSWs are initiated over a period of a few days, giving

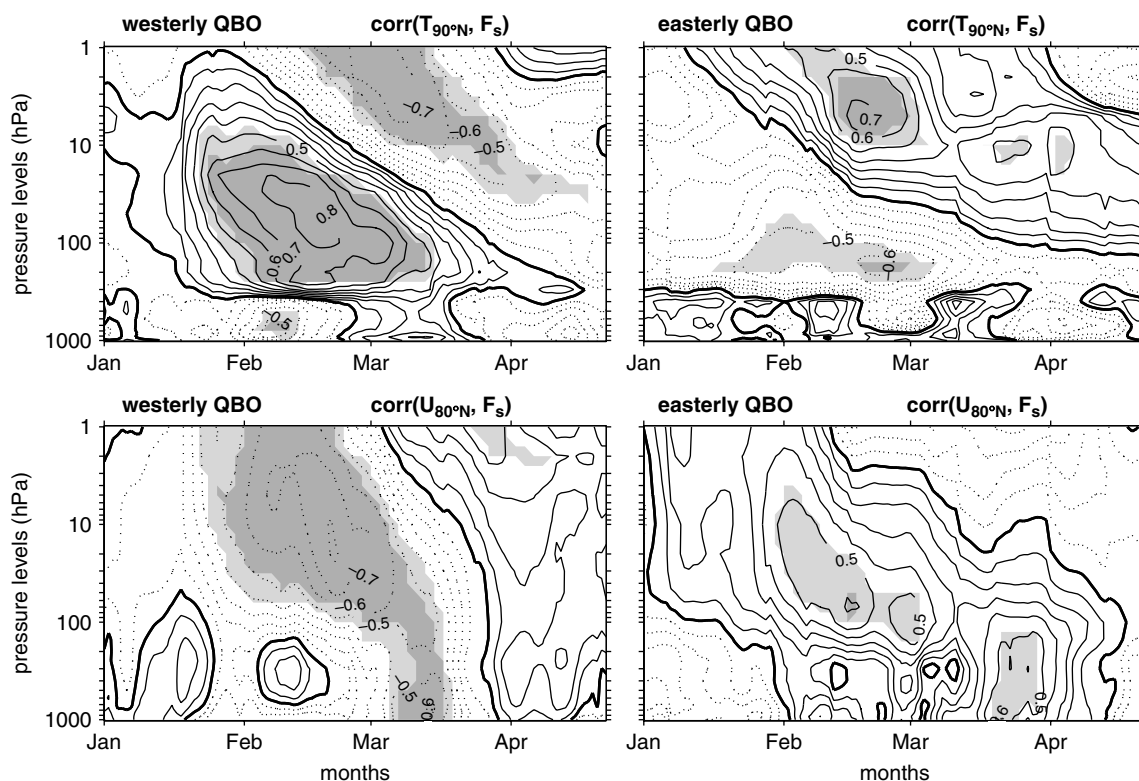


Figure 5. Running correlations between the 6-month averaged F_s and temperature at 90°N (upper row), and zonal wind at 80°N (lower row), under wQBO (1st column) and under eQBO (2nd column), displayed in time-height cross-section. The QBO, polar temperature and zonal-mean zonal wind are averaged using a 10-day running window and F_s is defined as 6-month averaged values of F10.7 cm solar radio flux preceding the averages of atmospheric variables. Solid and dashed contours represent positive and negative correlation and the thick black contour is zero correlation. The contour interval is ± 0.1 . The light and dark shaded areas indicate that the correlations are statistical significant with confidence level $\geq 90\%$ and $\geq 95\%$, respectively. Similar results can be obtained from 65°N poleward.

rise to anomalously warm conditions and the destruction of the vortex throughout the depth of the stratosphere. The subsequent recovery to westerly/colder conditions is governed by radiative cooling (Limpasuvan *et al.*, 2004), the time-scale of which depends on height; the polar vortex recovers first at upper levels where the radiative time-scale is relatively short (\sim days), but in the lower stratosphere where radiative time-scales are much longer, full recovery of the vortex takes correspondingly longer, thus explaining the gradual descent of the negative temperature correlations from 1 hPa in early February to \sim 100 hPa in mid-March.

The negative signals under eQBO in the lower stratosphere may correspond to more SSWs occurring in mid-winter of the LS/eQBO years. The weaker correlations earlier in the winter suggest more disturbed conditions with less 11-yr SC influence, in agreement with previous studies (Baldwin and Dunkerton, 1998; Gray *et al.*, 2004). From mid-January to March, strong positive signals appear in the upper stratosphere. These upper stratospheric signals are either due to subsequent recovery to westerly/colder conditions following the SSWs in mid-winter of the LS/eQBO years, or a result of a warmer response in temperature at HS similar to that under wQBO. If the latter case holds true, a QBO perturbation on the solar signals in the Arctic winter should be primarily confined in the lower stratosphere.

In the troposphere, there are also significant correlations under both QBO phases, especially in the zonal wind fields during March, possibly due to weaker winds in HS/wQBO years and LS/eQBO years. The correlations occur almost simultaneously at all heights below \sim 200 hPa in the wind fields and \sim 300 hPa in the temperature fields. This height dependence is similar to that of the northern annular mode (NAM) anomalies (Baldwin and Dunkerton, 2001) and is likely to reflect the faster time-scales of the typical dynamical processes in the troposphere.

Correlation analysis has been performed of F_s against progressing quasi-10-day averages of temperature and zonal wind in the latitude-height cross-section. Figure 6 shows the correlation between quasi-10-day averages of temperature in the NH and F_s preceding the date when the quasi-10-day temperature averaging starts, for the five winter months from November to March. The data are also grouped according to the phases of the QBO. Qualitatively similar results are obtainable if 5- to 20-day averages are used. Note that the use of quasi-10-day averages is only to facilitate an easier discussion of the results because the patterns can be described as early, middle and late solar signals for a given calendar month. The lack of radiosonde measurements in the upper stratosphere may result in unreliable estimations before the satellite era (i.e. pre- September 1978). For this reason, results from data since September 1978 are reported below. Discussions on sensitivity of the results to the period chosen are also made.

Figure 6 shows that, under wQBO, no solar signature can be found in polar temperature from 1 November to 20 January. Highly significant positive correlations start to

appear during 21–31 January in the extratropical upper stratosphere (2–8 hPa). From that time forward, those positive signals move slightly poleward but noticeably downward and finally descend into the polar troposphere in the 1–10 March panel. Simultaneously, significant poleward movement of the solar signals can be noticed near the Equator in the upper stratosphere. Starting from the 1–10 February panel, significant positive correlations start to build up near the Equator at \sim 3 hPa and then disperse poleward reaching 40°N in the 10–20 March panel.

Under eQBO, again no clear solar signature is found in the extratropical stratosphere from 1–10 November to 11–20 December. Negative correlations start to build up in the lower polar stratosphere from 21–31 December and they remain in the region until 1–10 March and ease away after then. Clear positive solar signals appear in the extratropical upper stratosphere in late January. Under eQBO, the solar signals appear to descend more slowly than those under wQBO. They remain above 30 hPa until 11–20 March after which they rapidly diminish and exhibit no noticeable poleward propagation.

Significant positive correlations are also present in the low to middle latitudes. In the lower stratosphere subtropics to midlatitudes (20°–50°N, 20–100 hPa), positive correlations are found throughout all winter months up to the beginning of March under wQBO. Under eQBO, during February strong positive correlations are present in the equatorial tropical latitudes, which are simultaneously accompanied by negative correlation in the subtropics, suggesting a modulation of the Hadley circulation (Haigh, 1996, 1999).

Figure 7 shows the corresponding zonal-mean zonal wind analysis. Under wQBO, there is no significant correlation until mid-January in the polar region, while significant positive correlations appear in the extratropical lower stratosphere with negative correlations at midlatitudes in the 11–20 January panel. Noticeable negative correlations appear in the subtropical to midlatitude upper stratosphere in the 21–31 January panel. By 1–10 February, the centre of these correlations has moved poleward from 35°N to 60°N, and by 11–20 February it has descended from 3 hPa to 30 hPa. From then, the downward propagation continues and it reaches the polar troposphere in the 1–10 March panel. Concurrently, significant positive correlations build up in the midlatitude upper stratosphere in early February and propagate more slowly poleward and downward until 1–10 March. Near the Equator, significant negative solar signals are found at \sim 2–5 hPa as early as 1–10 December, implying that the equatorial and subtropical zonal winds become more easterly under HS than under LS, and these remain throughout the winter.

Under eQBO and in the polar region, though positive correlations appear in the polar stratosphere across the winter months, they are mostly not significant at the 95% confidence level. From 11–31 January, negative correlations build up in the upper stratospheric subtropics and remain there until early February. In February, these negative correlations are noticeably enhanced, and significant correlations are extended into the midlatitude

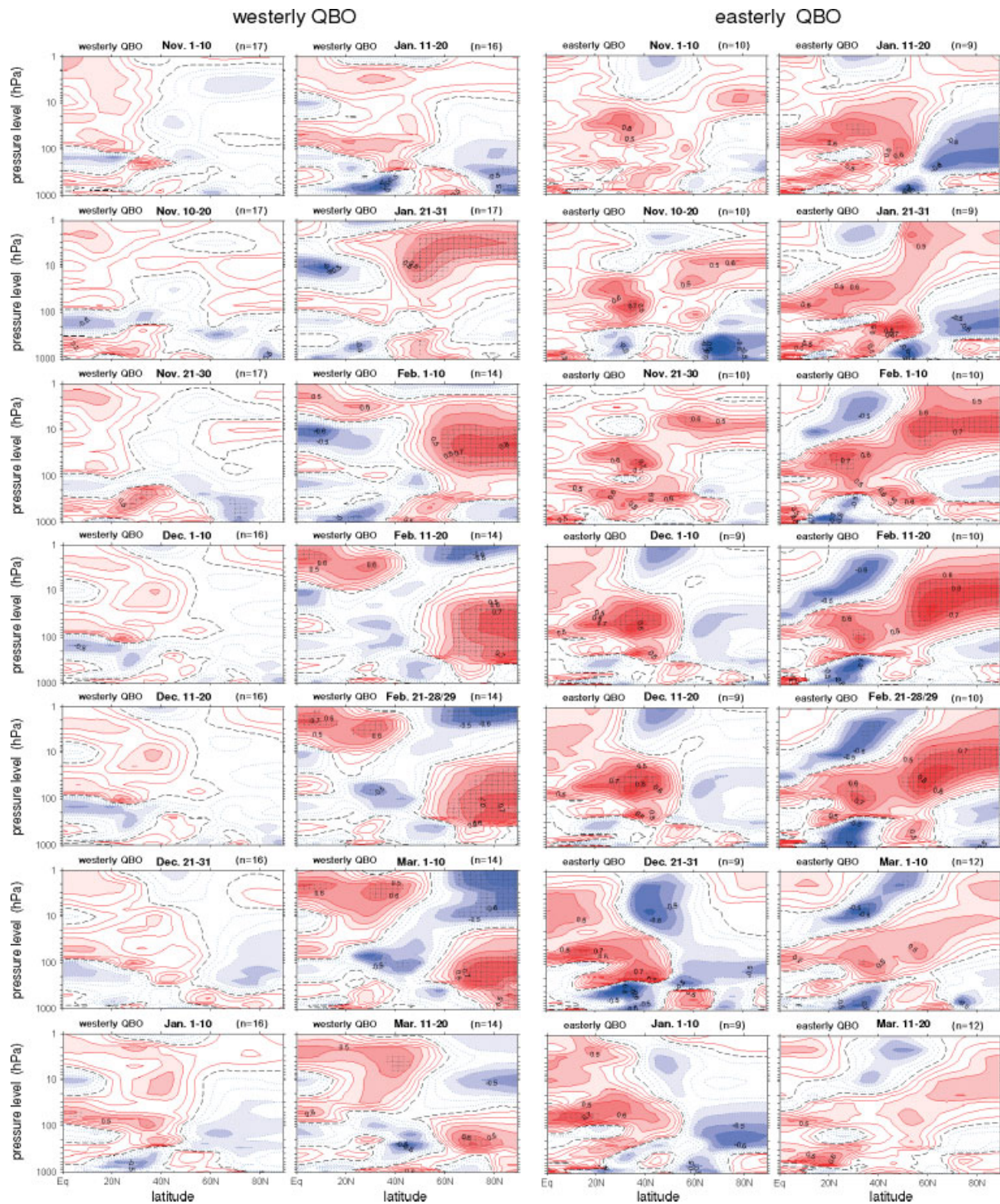


Figure 6. Seasonal progression of the correlations between the NH winter (November–March) temperature and 6-month averaged F10.7 cm solar flux, displayed in latitude–height cross-section. 1st and 2nd columns: QBO westerly; 3rd and 4th columns: QBO easterly; 1st and 3rd columns: period 1 November to 10 January; 2nd and 4th columns: 11 January to 20 March. The contours and shaded areas are the same as Figure 1.

upper stratosphere and troposphere. It is apparent that poleward propagation of the negative solar signals in the upper stratosphere is simultaneously accompanied by a strengthening of the positive–negative–positive (from Equator to Pole) pattern of correlations in the troposphere. From mid-January to late February, significant positive correlations appear in the tropical and subtropical

troposphere; generally opposite to those shown under wQBO. The correlation pattern in the equatorial to the subtropical troposphere under eQBO implies weaker westerlies in the equatorial flank of the Hadley cell and stronger westerlies in its poleward flank at HS. The negative then positive latitudinal correlation pattern in the extratropical region in February suggests a negative

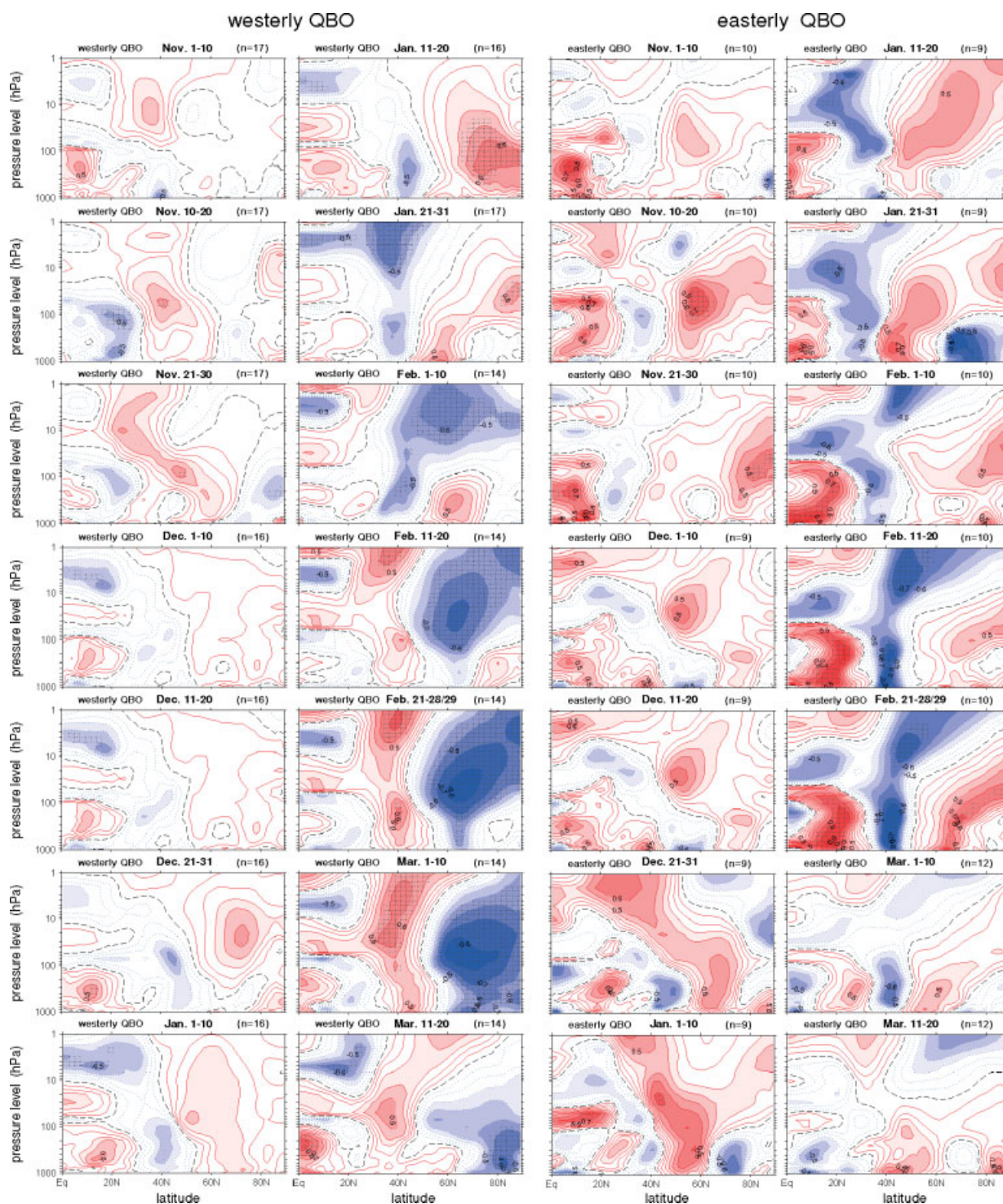


Figure 7. Same as Figure 6 but the temperatures are replaced by the zonal winds.

Northern Annular Mode (NAM) at HS, which is found to be associated with a warmer polar vortex (Thompson and Wallace, 1998; Baldwin, 2001); this is consistent in terms of thermal wind balance in relation to the solar signals in temperature shown in Figure 6. In comparison to those under wQBO, the strongest correlations are found in low to middle latitudes rather than near the Pole, and its descent rate in the polar region is noticeably slower under eQBO than under wQBO. This implies that dynamic responses to the 11-yr SC in the

lower stratosphere are stronger in the polar region under wQBO and in the extra-polar region under eQBO, supporting the conclusions of previous studies (Labitzke, 2005; Lu *et al.*, 2007). However, our results shown in Figures 5–7 differ from Kodera and Kuroda (2002), who found that westerly anomalies associated with the upper stratospheric subtropical jet moved poleward and downward under HS in early winter. We find that the early winter solar signals are no longer significant when more data are used.

3.2. Solar signals at low latitudes

It is known that the Tropics and extratropics are linked through the BD circulation, with upwelling in the Tropics and downwelling in the polar region. In the lower stratosphere, anomalous warming in the polar region is likely to be compensated by cooling in the subtropics and midlatitudes, due to the associated strengthening of the BD circulation. In order to investigate any possible interaction between tropical solar forcing and extratropical responses, in this section we focus on temperature variations in the equatorial to subtropical region of the stratosphere. The 2-month averages are used for the atmospheric variables, as we found that the signals at low latitudes are of lower frequency than those at high latitudes.

Figure 8 shows the composite differences between HS and LS conditions of December–January and February–March mean temperatures (using data from September 1978 onwards). The solar signal in stratospheric equatorial temperature during December–March essentially has a double-peaked vertical profile with the upper peak near 2–3 hPa and the lower peak at ~50 hPa; the signals are approximately symmetric about the Equator. The temperature is up to 3 K higher in the upper stratosphere and up to 1.5 K higher in the midlatitude lower stratosphere at HS than at LS. However, in the region of 25°–55°N in the upper stratosphere, up to 3 K reduction in temperature is found. The pattern of solar cycle temperature differences is consistent with the studies of Haigh (2003), Crooks and Gray (2005) and Keckhut *et al.* (2005), although the amplitudes are larger. This may be due to a contribution from the volcanic disturbances in the lower stratosphere but it is unlikely to be a factor in the upper stratosphere. A close examination of the statistical confidence levels suggests that the positive solar signature in the upper stratosphere achieves higher confidence levels in February–March than in December–January, while the opposite holds for the signals in the lower stratosphere.

On the time-scale associated with SSWs, temporal tendencies in tropical column ozone and temperature correlate inversely with the strength of planetary wave absorption at northern middle to high latitudes (Randel, 1993). Randel *et al.* (2002) showed that the positive effect of extratropical wave forcing on tropical upwelling exists from time-scales ranging from weekly to seasonal. In comparison to those early winter signals, the relatively weaker solar signals near the equatorial lower stratosphere in late winter are likely due to stronger wave forcing in the extratropics, therefore stronger equatorial lower stratospheric upwelling, at HS in late winter.

Figure 9 confirms that the QBO modulates the solar signals not only in the NH polar region but also at low latitudes. It shows the correlation between F_s Jul–Dec and $T_{\text{Dec–Jan}}$ (upper panels) and between F_s Sep–Feb and $T_{\text{Feb–Mar}}$ (lower panels), under wQBO (left-hand panels) and eQBO (right-hand panels), respectively, and suggests that the solar signals at low latitudes may also vary according to the QBO phase. In the upper stratosphere (1–5 hPa), the positive solar signals are stronger

under wQBO while in the lower to middle stratosphere (10–100 hPa), they are stronger under eQBO.

The QBO-modulated signals are shown clearly not only in the tropical lower stratosphere but also in the tropical upper stratosphere. The difference in the middle to lower stratosphere agrees well with Labitzke and van Loon (2000). The enhanced correlations in the upper stratosphere (at ~1–2 hPa) under wQBO and in the middle to lower stratosphere under eQBO can be understood in terms of the QBO-induced circulations (Plumb and Bell, 1982; Baldwin *et al.*, 2001), which are illustrated schematically by the grey arrows shown in the top row of Figure 9. In the upper stratosphere, the solar signals are likely to be radiatively driven as a result of irradiance changes and photolysis of ozone (Haigh, 1996). In wQBO years, there is anomalous relative QBO-induced descent over the Equator in the upper stratosphere (~2 hPa) with upwelling return arms in the subtropics. This results in additional adiabatic heating, thus reinforcing the positive solar signal near 2 hPa. In eQBO years the QBO-induced circulation is in the opposite sense to that in wQBO years and thus the solar signal is reduced in the equatorial upper stratosphere near 2 hPa. Just below this level, however, the QBO circulations reverse and the solar signal near 10 hPa is enhanced in eQBO years but minimized in wQBO years. Thus, the distributions of solar signals above 10 hPa shown in Figure 9 precisely reflect the modulations due to QBO-induced residual circulation.

In the lower stratosphere the solar signals are mainly dynamical in origin. A direct influence of dynamics on the temperature fields is reinforced by anomalous ozone transport at HS. An explanation of the anomalies in this region may involve SSWs and anomalous wave forcing in the polar region. In HS/wQBO years there are anomalously more SSWs occurring due to stronger poleward-propagating planetary waves, hence greater equatorial upwelling. The anomalously stronger equatorial upwelling under HS counteracts the anomalous wQBO descent. It results in weaker solar signals in the tropical lower stratosphere. In LS/eQBO years, there are also more SSWs occurring in the lower stratosphere, mainly due to stronger poleward wave forcing under eQBO (Holton and Tan, 1980, 1982; McIntyre, 1982; Lu *et al.*, 2008). However, the increased equatorial upwelling due to SSWs reinforces the anomalous QBO upwelling, and hence the overall solar influence is strengthened in the equatorial lower stratosphere. These different mechanisms acting at the different heights may explain the observed asymmetries in Figure 9 at all heights, in which the solar signals are enhanced in the upper stratosphere in wQBO years but are enhanced in the mid- and lower stratosphere in eQBO years. Nevertheless, it still does not explain why we observe more SSWs in HS/wQBO and LS/eQBO years in the mid- and lower stratosphere and why the planetary waves respond to the 11-yr SC differently in the early and late winters.

The physical processes discussed above suggest that the solar signal minimum at 10–30 hPa is a result of

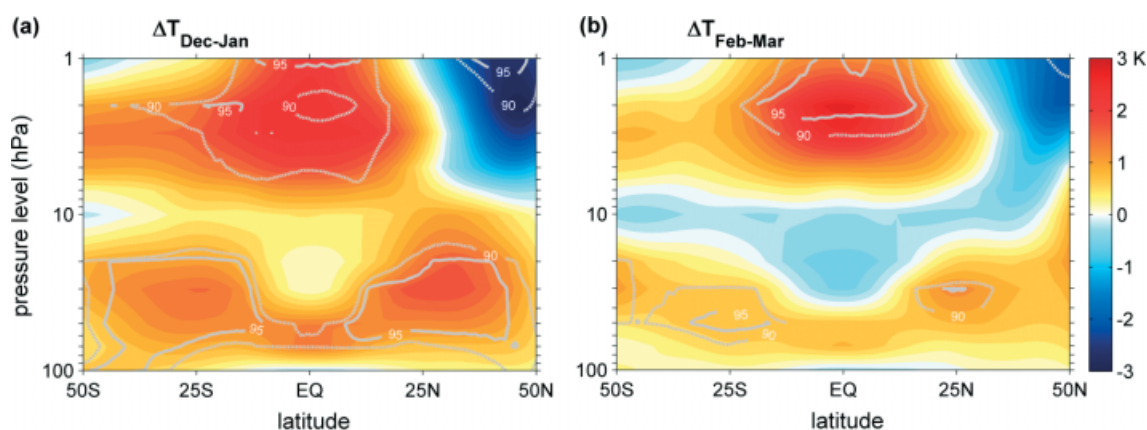


Figure 8. Composite differences between HS and LS for temperature ΔT (K, right-hand bar) for (a) the December–January mean, and (b) the February–March mean, displayed in the meridional–vertical cross-section of the stratospheric extra-polar region. The data are grouped into $\geq \bar{F}_s$ and $< \bar{F}_s$, where \bar{F}_s is July to December (in (a)) and September to February (in (b)) averaged F10.7 cm solar flux. The areas enclosed within the grey dashed and solid lines indicate that the differences are statistically significant from zero with confidence levels of 90% and 95%, respectively, calculated using a Monte-Carlo trial based non-parametric test.

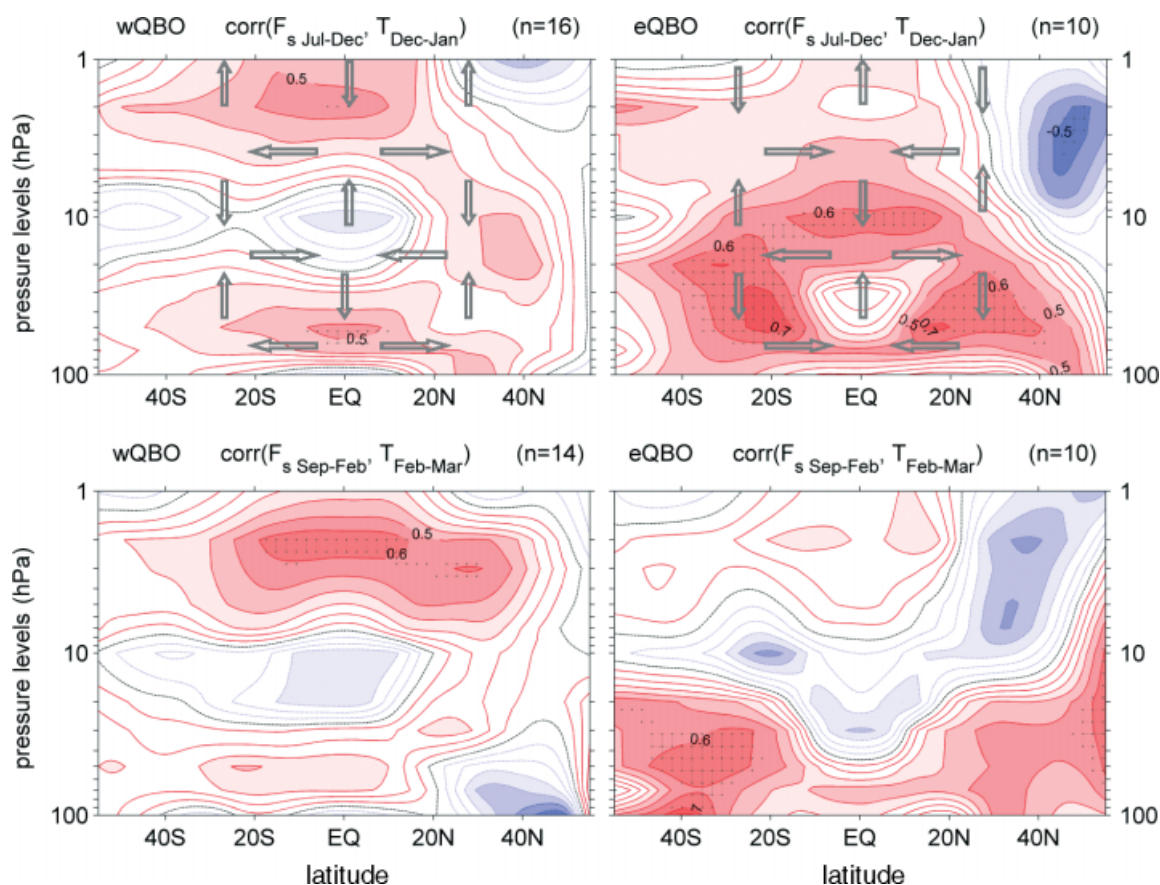


Figure 9. Correlations between December–January (1st row), and February–March (2nd row) mean temperature and 6-month averaged F10.7 cm solar flux, under wQBO (1st column), and under eQBO (2nd column), displayed in the meridional–vertical cross-section of the stratospheric extra-polar region. The contours and shaded areas are the same as Figure 1. The grey arrows shown in the top row panels illustrate the directions of the QBO-induced circulation.

different interactions between the QBO and the solar UV forcing in the upper and lower stratosphere. Lee and Smith (2003) have suggested that the lack of solar response in the tropical middle stratosphere is a result of linear superposition of two effects: the true solar response and the QBO contamination. Using a two-dimensional model, Smith and Matthes (2008) found that

the difficulty in isolating the solar cycle signals from the QBO signals lies in the fact that the QBO tends to lead to a periodicity which is interpreted by linear statistical analyses as a component of the solar cycle. The strong positive subtropical correlations in the lower stratosphere under eQBO suggest that increased equatorial ascent and subtropical descent is associated with the HS condition,

supporting an increased descent rate of the easterly shear zone during solar maximum (Pascos *et al.*, 2005). Salby and Callaghan (2000) suggested a nonlinear interaction between the 11-yr solar cycle and the QBO, and found that while the length of the easterly phase of the QBO was fairly constant, the westerly phase of the QBO varied according to the 11-yr solar cycle. However, Hamilton (2002), who examined 50 years of equatorial lower stratospheric wind observations from 1950 to 2000, found an apparent quasi-decadal variation in the duration of wQBO at 40–50 hPa, but it was not in phase with the 11-yr SC. Using radiosonde measurements for the period of 1953–2005, Fischer and Tung (2008) found the correlations between the duration of the QBO and the 11-yr SC for either phase of the QBO were close to zero. Compared to the period of 1957–1990, oppositely-signed correlations were found to exist in the pre-1957 and post-1991 periods. Thus, whether the 11-yr SC has a nonlinear, systematic influence on the QBO period length and descent speed remains inconclusive.

As demonstrated by considerably weaker correlations at low latitudes in Figures 1 and 3, further sensitivity tests using data from different time periods suggest weaker solar signals at low latitudes. This is largely because the temperature response in this region tends to be negative pre-1978 (not shown). It is unclear whether this is due to lack of quality data in the pre-satellite era, or to influences from other sources of variability. The ENSO, major volcanic eruptions and increase of carbon dioxide may also influence the tropical ascending part of the BD circulation. Differences in the rate of ascent will result in changes in lower-stratospheric ozone concentrations and adiabatic temperature in the equatorial lower stratosphere. Previous studies have suggested that major volcanic eruptions will not change the general character of the temperature response to solar UV forcing (Lu *et al.*, 2007). It is also unlikely for the ENSO to have a large influence on the solar signals at low latitudes as ENSO signals were found to be rather weak or negative in the lower stratosphere and insignificant in the upper stratosphere (Crooks and Gray, 2005; García-Herrera *et al.*, 2006; Camp and Tung, 2007). This apparent sign switch in temperature responses to solar forcing in the late 1970s might be related to a multi-decadal oscillation in the NH. For instance, Lu *et al.* (2008) reported substantially weakened QBO signals in the Arctic stratosphere in 1977–1997 and suggested a possible relation to the regime shift over the North Pacific. Further research is required to answer the questions as to whether and how a multi-decadal oscillation might modulate the temperature responses to solar forcing.

4. Conclusions

This study examines the life cycle of the original Labitzke and van Loon (1988) QBO-SC relationship in the Northern Hemisphere winter by using daily ERA-40 Reanalysis and ECMWF Operational data which extend

vertically to 1 hPa. It is found that the QBO-SC relationship holds in both temperature and zonal wind throughout the period 1958–2006 and the solar signals primarily occur in late winter (February to March). In temperature, positive solar signals are found in the lower to middle polar stratosphere under wQBO and in the upper polar stratosphere under eQBO. In zonal wind, negative signals are found in the middle to upper stratosphere under wQBO and at midlatitudes under eQBO.

Additional insights into the QBO-SC relationship are put forward by studying its seasonal evolution. While the stratospheric signals are found in late January to early March, the tropospheric signals take place primarily in late March and early April. This is a result of a poleward and downward movement of solar-induced anomalies since late January. In the Arctic winter, the life span of stratospheric solar signals is ~30–50 days, while it is ~10 days in the troposphere. Under wQBO, the polar stratospheric solar signals in zonal-mean zonal wind clearly lead and connect to those in the troposphere. In addition, the solar signals from the upper stratosphere tend to move faster and penetrate deeper down under wQBO than under eQBO.

Under wQBO, the solar perturbation on the NH winter circulation is likely to occur through its influence on SSWs in the polar region and compensating cooling at the Equator in the upper stratosphere. Under eQBO, the negative signals in the lower stratosphere are likely due to more SSWs occurring in eQBO/LS years; a process similar to that under wQBO might hold true in the upper stratosphere. Thus, the strong solar signals in the upper to mid-polar stratosphere under eQBO represent a combined effect of recovery from SSWs occurring under eQBO/LS and positive temperature responses in the upper stratosphere during the HS years.

Changes in the stratospheric polar region are primarily driven by anomalous wave forcing and residual circulation, which can be influenced either by internally generated dynamical perturbations of the atmosphere (e.g. the ENSO and the QBO) or by external forcing (solar, volcanic eruption or increase of carbon dioxide). We find that the QBO-SC relationship becomes clearer when the ENSO is not strongly negative and such an ENSO perturbation effect is more noticeable under eQBO than under wQBO. The relatively short data record poses a substantial challenge to properly separate ENSO influences from the QBO-modulated solar signals, as those effects are likely to be coupled nonlinearly through their effects on the planetary waves and therefore the residual circulation.

At low latitudes, positive solar signals are found in the stratospheric temperature fields, regardless of the QBO phase. The signals tend to have a longer life span (~3–4 months) and are characterized by a vertical double-peaked structure. The location and the magnitude of the positive equatorial response are in general agreement with previous studies (Crooks and Gray, 2005; Keckhut *et al.*, 2005; Remsberg and Deaver, 2005). For the first time, however, we find that the lower stratospheric solar signals tend to be stronger in early

winter but weaker in late winter. This is likely due to more waves being refracted toward the polar stratosphere at HS in late winter.

The solar signals at low latitudes are found to also vary according to the QBO phase. The temperature response in the lower stratosphere agrees well with that shown previously by Labitzke (2004, 2005), who reported a similar QBO-SC modulation in the same region during the NH summer. Here we suggest that the significantly enhanced solar signals in the upper stratosphere (at $\sim 1\text{--}2$ hPa) under wQBO and in the middle to lower stratosphere under eQBO can be explained in terms of the QBO-induced circulations in the upper stratosphere, and combined effects of SSWs and QBO-induced circulation in the lower stratosphere.

Further sensitivity tests suggest that, while the polar QBO-SC relationship remains stable for the entire period of 1958–2006, the signals in low-latitude temperature appear to be only significant when data from the satellite era are used. Longer data records and a better understanding of the interaction between solar forcing and various types of atmospheric variability are needed to determine the exact magnitude and structure of solar responses in temperature near the Equator.

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