JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D13101, doi:10.1029/2010JD015427, 2011

The vertical connection of the quasi-biennial oscillation-modulated 11 year solar cycle signature in geopotential height and planetary waves during Northern Hemisphere early winter

Ingrid Cnossen[1,2] and Hua Lu[1]

Received 2 December 2010; revised 28 March 2011; accepted 6 April 2011; published 2 July 2011.

[1] We analyzed observational geopotential height data to provide some new insights on the 11 year solar cycle signal in the Northern Hemisphere early winter and its modulation by the quasi-biennial oscillation (QBO). The signals are strongest in the upper stratosphere. When the QBO is in its easterly phase (QBOe), it appears to move gradually eastward and poleward, resulting in a predominantly positive signal over the pole, with a weaker vertically connected negative signal over the Icelandic Low. When the QBO is in its westerly phase (QBOw), the polar stratospheric signal is mainly negative and appears connected to a negative anomaly in the troposphere over the Aleutian Low. A spectral analysis of the stratospheric response in planetary waves showed a reduction of wave number 2 power under QBOe and an enhancement of wave number 3 under QBOw. These responses are characterized by an overall increase/decrease in wave activity at middle to high latitudes rather than a latitudinal shift of wave activity. There is no clear stratosphere-troposphere connection under QBOe, but under QBOw, there is a vertically coherent increase in wave power at wave numbers 1–3 with a period of 5.6–6.9 days. We suggest that the differences in response under QBOe and QBOw can be explained through differences in initial vortex strength, resulting in either a stronger influence from the low-latitude upper stratosphere (QBOe) or from the troposphere (QBOw) on the polar stratosphere.

Citation: Cnossen, I., and H. Lu (2011), The vertical connection of the quasi-biennial oscillation-modulated 11 year solar cycle signature in geopotential height and planetary waves during Northern Hemisphere early winter, *J. Geophys. Res.*, *116*, D13101, doi:10.1029/2010JD015427.

1. Introduction

[2] Many observational studies have shown the influence of the 11 year solar cycle (SC) on the stratosphere [e.g., *Labitzke*, 1987; *Labitzke and van Loon*, 1988; *Kodera and Kuroda*, 2002; *Crooks and Gray*, 2005; *Lu et al.*, 2007, 2009; *Frame and Gray*, 2010]. It is generally accepted that ultraviolet (UV) radiation, which varies by a few percent over the 11 year cycle, in interaction with the ozone in the upper equatorial stratosphere is responsible for the solar influences observed in the low-latitude stratosphere [*Haigh*, 2003; *Hood*, 2004; *Lean*, 2005]. It has been proposed that the changes in temperature and zonal wind structure induced in this way may, in turn, affect the polar region via a modulation of the vertical propagation of planetary waves from the troposphere into the stratosphere [*Kodera and Kuroda*, 2002]. This dynamic mechanism has been put forward to explain the poleward and downward propagation of the solar signals that is observed during the winter months [*Kodera and Kuroda*, 2002; *Matthes et al.*, 2004, 2006].

[3] Solar signatures have also been found within the troposphere [e.g., *Gleisner and Thejll*, 2003; *Gleisner et al.*, 2005; *Haigh et al.*, 2005; *Lu et al.*, 2007; *Frame and Gray*, 2010]. The mechanism responsible for these signals is not yet clear. Some studies have argued for a downward propagation of the solar-induced temperature anomaly in the lower stratosphere, which causes changes in synoptic scale waves near the tropopause [*Haigh et al.*, 2005; *Simpson et al.*, 2009]. Another possibility is that the polar stratospheric response propagates further into the troposphere via an effect on the Northern Atlantic Oscillation (NAO) [*Kodera and Kuroda*, 2005; *Hameed and Lee*, 2005] or on midwinter stratospheric sudden warmings (SSWs) [*Gray et al.*, 2004; *Cnossen et al.*, 2011]. These are referred to as “top-down” mechanisms [*Gray et al.*, 2010]. Others have suggested that solar-induced changes may form directly within the troposphere, through air-sea-radiative coupling at the ocean surface in the tropics, whereby the spatial asymmetries of solar forcing, induced by cloud distributions, results in greater evaporation in the subtropics and consequent moisture transport into the tropical convergence zones [*Meehl et al.*, 2003; *van Loon et al.*, 2007; *Meehl et al.*, 2008]. Such changes might then propagate upward to affect the strato-

[1]British Antarctic Survey, Cambridge, UK.
[2]Now at National Center for Atmospheric Research, Boulder, Colorado, USA.

0148-0227/11/2010JD015427

sphere, for instance through changes in the annular mode and/or the generation of upwardly propagating planetary waves. This is a so-called "bottom-up" mechanism. A modeling study by *Meehl et al.* [2009] showed that a coupling of the top-down and bottom-up mechanisms may amplify the initially small effect of the 11 year SC and result in a detectable perturbation on the regional and global circulation.

[4] In the polar stratosphere, the solar signatures have been found to be modulated by the quasi-biennial oscillation (QBO) of the equatorial stratospheric winds. *Labitzke* [1987] and *Labitzke and van Loon* [1988] found that the polar lower stratospheric temperature is positively correlated with the 11 year SC when the QBO is in its westerly phase (QBOw), while it is negatively correlated when the QBO is in its easterly phase (QBOe) [see also *Naito and Hirota*, 1997; *Gray et al.*, 2004; *Labitzke*, 2005; *Labitzke et al.*, 2006]. These alternating correlations with the 11 year SC over the Northern Hemisphere (NH) polar region cancel in the entire record composed of both QBOw and QBOe conditions and make the solar signal there virtually undetectable.

[5] Most studies of the QBO-modulated solar signal so far have been based on monthly averages of temperature or geopotential height fields, which provide limited information on the temporal evolution of the signals. *Lu et al.* [2009] recently investigated the development of the signals in more detail by using daily data from the European Centre for Medium-Range Weather Forecasts (ECMWF) extending from 1958 to 2006. They found that the stratospheric zonal-mean signal first appears in the upper stratosphere in January for both QBO phases and moves poleward and downward as winter progresses. In the troposphere, they found a negative temperature response to the 11 year SC, which starts in the high-latitude regions in November [see *Lu et al.*, 2009, Figure 6], again for both phases of the QBO. However, as their study was based on zonal mean data, they could not determine exactly where these signals originated. Their results could not determine either whether or not the early winter signal in the troposphere has a cause-effect relationship with the middle to late winter stratospheric responses, possibly because the solar signal is not zonally uniform. Indeed, recent studies have indicated that the tropospheric solar signal is longitudinally variable and is particularly strong over the Pacific Ocean [*Berg et al.*, 2007; *Barriopedro et al.*, 2008; *Woollings et al.*, 2010] and the eastern Atlantic Ocean [*Barriopedro et al.*, 2008; *Woollings et al.*, 2010; *Lockwood et al.*, 2010]. However, it is not clear how the longitudinal patterns may be altered under different QBO phases in the troposphere and stratosphere, although *Barriopedro et al.* [2008] found that solar influences on the NH winter blocking are stronger under QBOw than under QBOe.

[6] Both the QBO and solar forcing are thought to have an effect on planetary wave activity. *Holton and Tan* [1980, 1982] first proposed that the equatorial lower stratospheric QBO modifies the stratospheric waveguide for vertically propagating planetary waves by displacing the zero-wind line, the critical line for stationary waves, such that more waves are deflected toward the pole during QBOe, resulting in a warmer and weaker, more disturbed polar vortex. *Kodera and Kuroda* [2002] proposed a similar mechanism to explain the poleward and downward propagation of the solar signal from the low-latitude stratosphere into the polar stratosphere. They argued that the temperature and zonal wind anomalies in the equatorial upper stratosphere resulting from direct solar UV forcing cause more planetary waves to be deflected from the subtropics during solar maximum. The changes in planetary wave forcing then bring about further changes in zonal wind, resulting in a gradual poleward and downward propagation of the anomalies.

[7] This mechanism has been supported by both observational and modeling studies through the analysis of Eliassen-Palm (EP) flux diagnostics [*Kodera and Kuroda*, 2002; *Matthes et al.*, 2004, 2006; *Cnossen et al.*, 2011]. In general, there is evidence that the equatorial upper stratosphere might play a critical role in influencing the extratropical stratospheric circulation during the NH winter [*Gray et al.*, 2001a, 2001b; *Gray*, 2003]. *Gray* [2003] and *Rigby* [2010] proposed that this is due to planetary waves with a very deep vertical structure, encompassing the whole depth of the stratosphere. However, there is little other information on the characteristics of the waves that might be involved. This is because EP flux diagnostics only provide information on the total wave activity in a zonally averaged sense.

[8] Studies that investigated the changes in the planetary waves in more detail have given inconclusive results so far. *Soukharev and Labitzke* [2001] used the geopotential height and temperature data from the Stratospheric Research Group of Free University of Berlin (FUB) for 1965–1998 (30 hPa) and 1965–1996 (10 hPa) to investigate the response of planetary waves to solar forcing. They focused on periodicities associated with the Sun's rotation period (27.2 days) and found a significant increase under solar maximum conditions for the 54.4 day periodicity in wave number 1 (twice the solar rotation period) and for the 27.2 and 25.3 periodicities in wave number 2 (the latter resulting from the interaction between the solar rotation period and the annual cycle). The changes were found both at 10 and 30 hPa and were most pronounced at midlatitudes (40°–60°N). No latitudinal shift in wave activity was reported. *Salby and Callaghan* [2004] used the National Center for Environmental Prediction's (NCEP) data from 1955 to 2000 to examine the variation in temperature, zonal wind, and geopotential height associated with the 11 year SC in the NH winter stratosphere. They found an anomalous wintertime tendency (difference between February and September) of the 30 hPa geopotential height operating coherently with the 50 hPa equatorial wind and F10.7 solar flux. This consisted of a weakening of the Aleutian High (which corresponds to the Aleutian Low in the troposphere) at midlatitudes and a strengthening at high latitudes for low solar activity under QBOe conditions (LS/QBOe) and for high solar activity under QBOw conditions (HS/QBOw). They interpreted their findings as a poleward shift of wave number 1 for those conditions. *Berg et al.* [2007] used the NCEP geopotential height data from 1965 to 1997 to study differences in planetary wave numbers 1–3 in the upper troposphere (300 hPa) in relation to the 11 year SC. They showed an equatorward shift and amplitude decrease of wave number 1 for high solar activity in December, which weakened in January and February. In January and February, wave number 2 showed the strongest change, consisting of an increase in amplitude and an eastward and poleward shift for high solar activity, while

Table 1. The Years Assigned to Each Composite Data Set[a]

QBOe		QBOw	
LS (9)	HS (7)	LS (16)	HS (11)
1962	1958	1961	1959
1965	1960	1963	1967
1974	1968	1964	1969
1977	1970	1973	1978
1984	1979	1975	1980
1994	1989	1976	1982
1996	2001	1985	1988
2005		1986	1990
2007		1987	1999
		1993	2000
		1995	2002
		1997	
		2004	
		2006	
		2008	
		2009	

[a]The total number of years in each data set is given in parentheses.

planetary wave number 3 did not show significant changes. *Tourpali et al.* [2003] performed a study with a coupled chemistry-general circulation model (MAECHAM4/CHEM) on the effect of the 11 year SC in UV radiation. Their model simulation showed that wave number 1 is favored at the cost of wave numbers 2 and 3 in the NH winter troposphere, while wave number 1 is weaker in the stratosphere. The effect of the QBO was not considered by their model simulations.

[9] In this study, we will investigate the QBO-modulated solar signatures in the troposphere and stratosphere in more detail, both considering the responses of the mean field and of the planetary waves. We carry out an analysis based on an extended observational data set from 1958 to 2009 to (1) provide further details of the longitudinal variation, vertical connection, and temporal evolution of the QBO-modulated 11 year SC signals and (2) clarify which planetary wave numbers and periods show a significant response to the 11 year SC under the two QBO phases. We also examine whether there are any latitudinal shifts in wave activity, as expected if the *Kodera and Kuroda* [2002] mechanism is responsible for the QBO-modulated responses. Because the interaction between planetary waves and the QBO is distinctly different for early and late winter [*Holton and Tan*, 1980, 1982; *Hu and Tung*, 2002; *Naito and Hirota*, 1997; *Naoe and Shibata*, 2010], we focus solely on early winter (October–November–December (OND)) in this study. The aim is to gain further insights in the initial development of the solar signal and the role of early winter planetary wave activity in preconditioning the stratospheric responses in late winter detected by previous studies [e.g., *Lu et al.*, 2009].

2. Data and Methods

[10] We used the 6 hourly geopotential height field at 2.25° × 2.25° spatial resolution from the ERA-40 data set by the ECMWF [*Uppala et al.*, 2005] for 1958–2001, extended with the ECMWF ERA-Interim data [*Dee and Uppala*, 2009; *Simmons et al.*, 2007] for 2002–2009. While it is not ideal to merge two data sets derived from different data assimilation models, we have done this here in order to maximize the length of the data set, as needed for the study of 11 year SC signals. It also means that data from the presatellite era have been included, which are known to be less reliable. We have performed various checks by excluding parts of the data from our analysis to ensure that the results remain at least qualitatively similar.

[11] A composite analysis, in which the data were separated into HS and LS activity conditions for both phases of the QBO, was carried out. This was done at four different pressure levels, of which two were in the stratosphere (10 and 50 hPa) and the other two were in the troposphere (200 and 500 hPa). The full meridional and zonal structure of the difference in geopotential height between HS and LS during early winter (OND) was studied. Differences were taken for a sequence of overlapping 30 day intervals with a moving window of 10 days, allowing us to investigate the temporal evolution of the responses and their possible vertical connections. The same analysis was also carried out for the ERA-40 data only to check that results were consistent with those found for the extended data set. As the results are rather similar, we only report the results from the extended data set here, but differences are noted in the text where needed.

[12] Our investigation of planetary wave responses to the 11 year SC is based on a temporal-spatial spectral analysis. This analysis was also performed for each of the four pressure levels and for each QBO phase and made use of the data for the 90 days following the 1 October inclusive. When we report the results of the spectral analysis, we concentrate on the results for 10 and 200 hPa, as the results for 50 and 500 hPa were found to be quite similar to those for 10 and 200 hPa, respectively.

[13] Following *Lu et al.* [2009], the daily observed 10.7 cm solar radio fluxes obtained from the National Geophysical Data Center website (http://www.ngdc.noaa.gov/stp) were used as an indicator for the 11 year SC. To focus solely on the effect of the 11 year cycle, a 365 day low-pass filter was applied to the solar radio fluxes to eliminate higher-frequency variations. The mean value for October of the filtered time series is denoted as F_{Oct} hereafter and was used in the analysis to define the HS and LS conditions. Very similar results are obtained if the October to December mean is used to define the HS and LS conditions, as the filtered time series only varies slowly over a decadal time scale. The mean F_{Oct} over all years (1958–2009) and the 95% confidence interval on that mean were calculated. Any year for which F_{Oct} was higher than its mean plus the 95% confidence interval was assigned to the HS condition, and any year for which it was below the mean minus the 95% confidence interval was assigned to the LS condition.

[14] The QBO was defined using the deseasonalized zonal wind from the blended ERA-40 and ERA-Interim data at 0.56°N, 50 hPa, consistent with previous work [*Holton and Tan*, 1980; *Labitzke*, 2005; *Lu et al.*, 2009; *Naoe and Shibata*, 2010]. The mean value for OND was used to divide the data into QBOe and QBOw in the same way as was done for HS and LS using F_{Oct} as described above. Composite differences between the HS and LS data sets were then calculated for QBOe and QBOw separately, and the significance was estimated with a Student's *t* test. The years assigned to each of the composites are given in Table 1.

[15] For our spectral analysis, the space-time Fourier decomposition introduced by *Hayashi* [1971, 1979] was applied to the geopotential height data. This method has

recently been applied to both observational and model-simulated data sets by *Dell'Aquila et al.* [2005, 2007] and *Lucarini et al.* [2007]. A Fourier decomposition on its own does not distinguish between standing and traveling waves: a standing wave results in two spectral peaks corresponding to traveling waves moving eastward and westward with the same speed and phase. To distinguish between traveling and standing waves, the Hayashi method assumes complete statistical coherence between the easterly and westerly components of standing waves. The incoherent part of the spectra is then attributed to real traveling waves. As any assumption, this is not without drawbacks: the incoherent part of the spectra will include what some might prefer to call noise [e.g., *Schäfer*, 1979]. However, we follow the notion of *Hayashi* [1971, 1979] and *Mechoso and Hartmann* [1982] that this part of the spectrum can be interpreted as eastward and westward propagating waves. In our results, we have followed the conventions adopted by *Lucarini et al.* [2007] and multiplied the obtained spectra by $k_j\omega_m\tau/2\pi$, where $k_j = 2\pi j$, $\omega_{\mathrm{m}} = 2\pi m/\tau$, and $\tau = 90$ days (the length of the season). Index j is the wave number, and index m is a frequency index. The obtained power spectrum is in units of m^2.

[16] The Hayashi spectra were first calculated for area-weighted averages of the geopotential height over 10° wide latitude bands from the equator toward the pole for each pressure level. Differences of the power spectra between HS and LS conditions were then taken, both for QBOe and QBOw, and the significance was tested using a Student's t test. This provided information on the main significant changes in the planetary wave spectrum in terms of the wave numbers and periods and the latitude bands that showed the most significant changes. On the basis of those results, the latitude bands with the largest significant changes were aggregated in a single latitude band. Only the composite difference of the power spectra for this aggregated latitude band is reported here.

[17] Second, the Hayashi spectra were calculated for each individual latitude to investigate if any latitudinal shifts in wave activity occurred within those subdomains of the spectrum that showed significant difference between HS and LS conditions. We also report whether standing, eastward propagating, or westward propagating waves are primarily responsible for the detected change. Only changes that were significant in both the full data set from 1958 to 2009 and the ERA-40 data set from 1958 to 2001 were considered.

3. Results

3.1. Solar Signal in the Mean Geopotential Height

[18] Figure 1 shows the composite difference in the mean OND NH geopotential height between the high and low solar activity composites ($Z_{\mathrm{HS\text{-}LS}}$), for QBOe (Figure 1, left) and QBOw (Figure 1, right), at 10, 50, 200, and 500 hPa (Figures 1a–1d). It is immediately evident that the height response $Z_{\mathrm{HS\text{-}LS}}$ is different for QBOe and QBOw in both the stratosphere and the troposphere. The strongest significant signals are found under QBOe and in the stratosphere. At 10 hPa and under QBOe conditions, $Z_{\mathrm{HS\text{-}LS}}$ is predominantly positive, implying a warmer, more disturbed vortex. A similar predominantly positive response pattern can also be seen at 50 hPa. Under QBOw conditions, the height response $Z_{\mathrm{HS\text{-}LS}}$ is statistically weaker in comparison to that for QBOe for all four pressure levels. In the stratosphere, the longitudinal pattern of $Z_{\mathrm{HS\text{-}LS}}$ under QBOw consists of a negative cell over the pole, with positive cells at lower latitudes that are primarily centered over northeastern Europe and the west Siberian plain (~40°E) and off the northeastern coast of America (~160°W).

[19] For both QBO phases, the signals become progressively weaker, less significant, and more zonally varying when we move from the upper stratosphere to the lower stratosphere and into the troposphere. Despite the weaker signals, a few key features are consistently present for all four pressure levels. Under QBOe, a significant positive cell persists over northeastern Asia (~120°E) that can be followed all the way from 500 hPa up to 10 hPa, although at 10 hPa, the significant portion is located further westward. A negative cell over the Arctic Ocean and northwestern Russia can be followed from 500 hPa up to 50 hPa. Negative $Z_{\mathrm{HS\text{-}LS}}$ signals in the troposphere are also found in the east coast of China and the eastern part of Canada. Under QBOw, the most consistent vertical connection is marked by a negative $Z_{\mathrm{HS\text{-}LS}}$ cell over northeastern Asia, although the response is statistically significant only in the lower stratosphere (from 50 to 200 hPa).

[20] In order to study how these longitudinally varying signals evolve over time, Figures 2 and 3 each show sequences of 30 day moving averages of $Z_{\mathrm{HS\text{-}LS}}$ with a 10 day forward shift for QBOe (Figure 2, left to right) and QBOw (Figure 3, left to right). For each pressure level (Figures 2a–2d and 3a–3d), the analysis starts on 1 October and ends on 29 December. Again, the time evolution of $Z_{\mathrm{HS\text{-}LS}}$ shows distinctly different spatial patterns under QBOe and QBOw, and the broadscale response at high latitudes may well be described as opposite. However, the details of the oppositions show certain regional preferences, and those regional "hot" or "cold" spots are, in many cases, vertically connected.

[21] In the stratosphere, the geopotential height response pattern associated with the 11 year SC under QBOe is dominated by a positive cell that broadly spreads over North America and Canada, the Pacific Ocean, and northeastern Asia during October and November (90°E–90°W). It forms a belt at low latitudes that moves poleward and/or eastward as the winter progresses. The positive cell over northeastern Asia appears to connect into the troposphere up to 31 October to 29 November. From 10 November to 9 December onward, the structure of the signal changes and its vertical connection becomes less obvious. In addition, there is a negative response region present during October and November over northwestern Europe and the North Atlantic Ocean, corresponding to the eastern part of the Icelandic Low. This negative cell is statistically significant at 50 hPa and can be followed down into the troposphere, where it remains present until 31 October to 29 November. The significant portion of this negative cell moves further eastward and poleward as we move from the stratosphere into the troposphere and as winter progresses.

[22] Under QBOw, the responses at 10 and 50 hPa are of similar magnitude as for QBOe, but the sign of $Z_{\mathrm{HS\text{-}LS}}$ is largely opposite at high latitudes (see Figure 3). The longitudinal structure of the signal changes more strongly over time than for QBOe, so that it partly cancels itself out when the average is taken over OND. This is the reason that the signal appeared much weaker in Figure 1 in comparison to

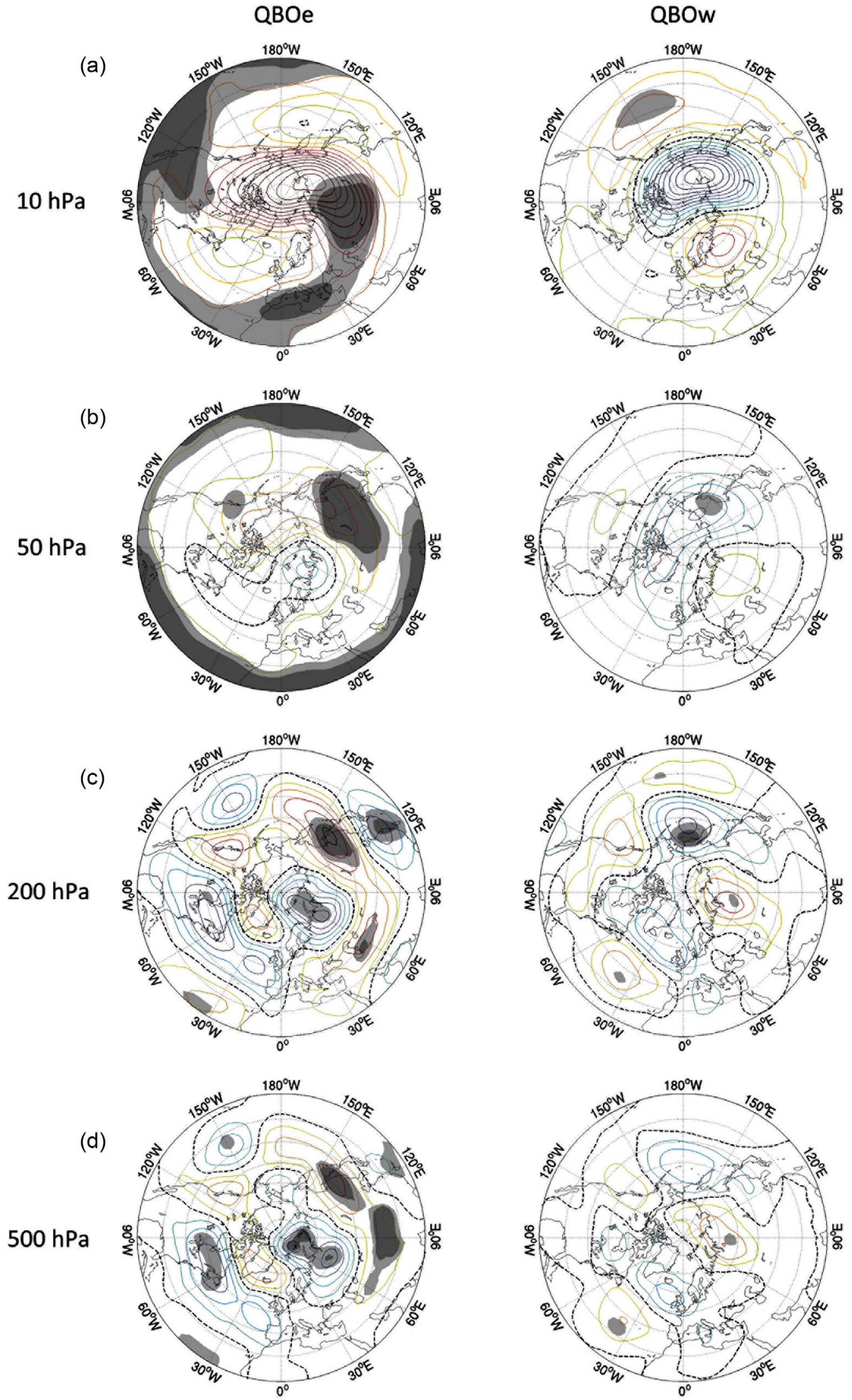

Figure 1. Difference in geopotential height between HS and LS for (left) QBOe and (right) QBOw at (a) 10, (b) 50, (c) 200, and (d) 500 hPa from 20°N to 90°N for OND. The contour interval is 15 m for 10 and 50 hPa and 10 m for 200 and 500 hPa. The light (dark) shading indicates significance at the 90% (95%) level.

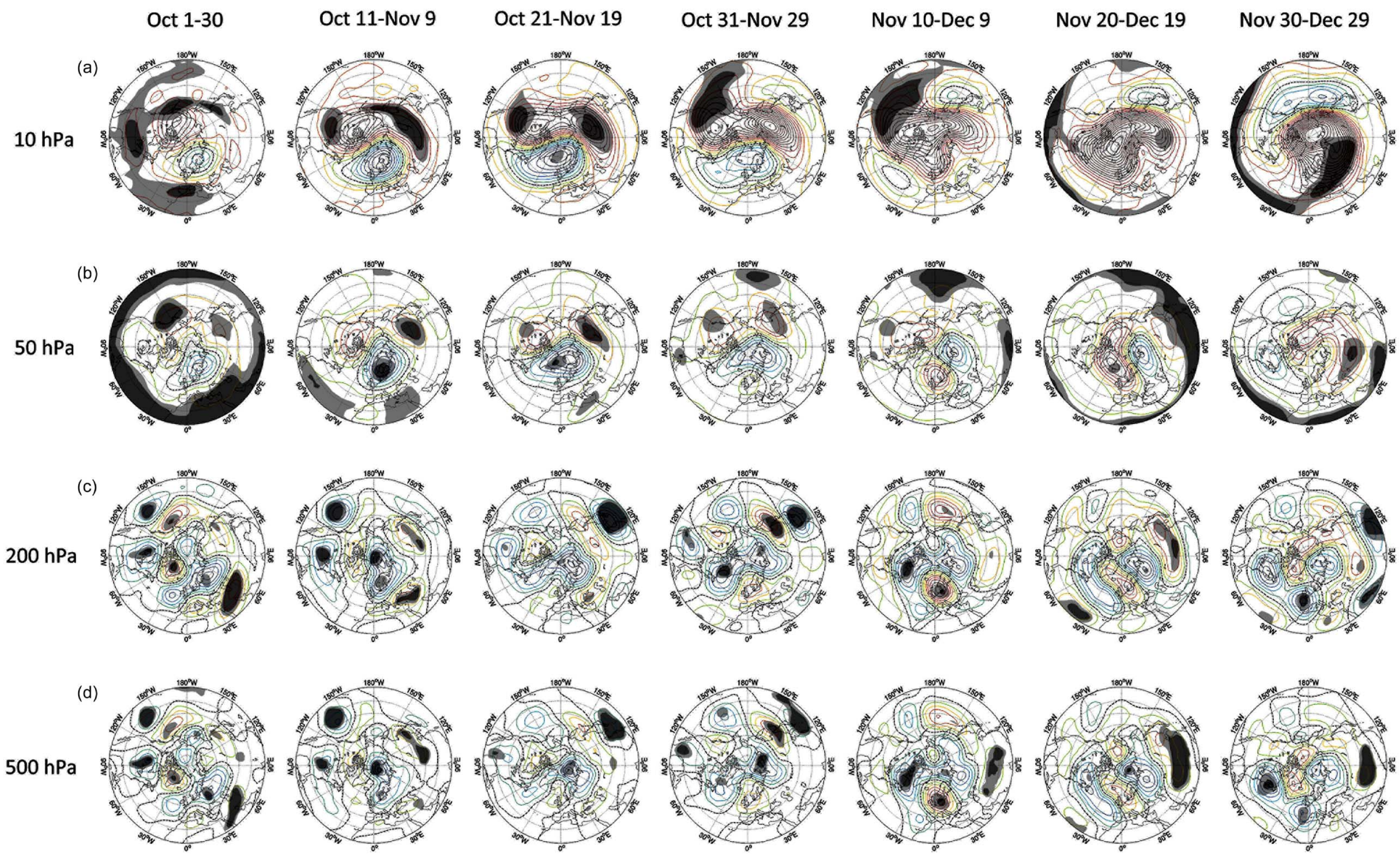

Figure 2. Difference in geopotential height between HS and LS for 30 day running averages with a 10 day shift from (left to right) 1 October to 29 December at (a) 10, (b) 50, (c) 200, and (d) 500 hPa from 20°N to 90°N for QBOe.

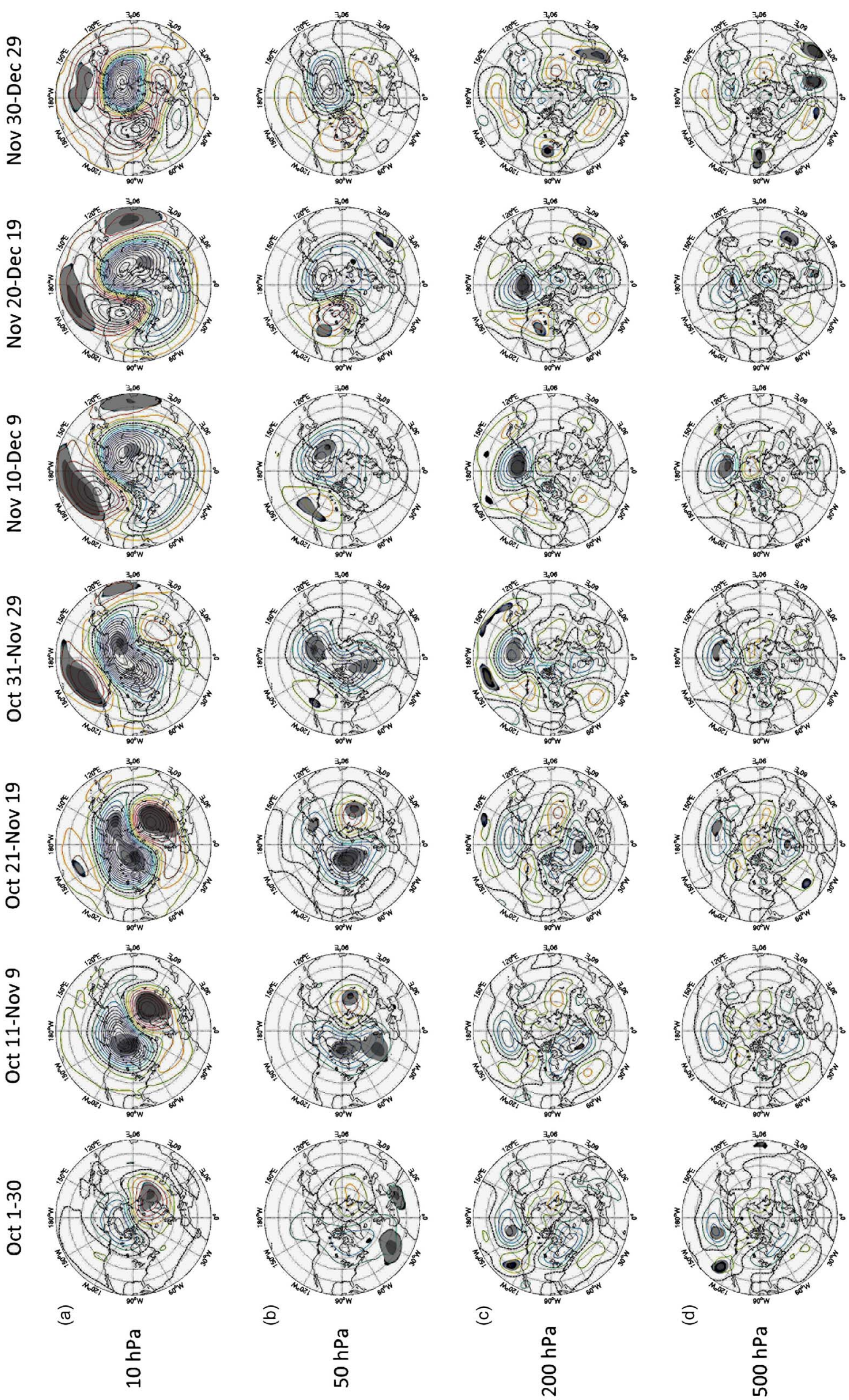

Figure 3. Difference in geopotential height between HS and LS for 30 day running averages with a 10 day shift from (left to right) 1 October to 29 December at (a) 10, (b) 50, (c) 200, and (d) 500 hPa from 20°N to 90°N for QBOw.

that under QBOe, and it might signify a stronger longitudinal disturbance under HS/QBOw at midlatitudes. In October to early November, the high-latitude response at 10 hPa is marked by a semipermanent, negative cell extending from Canada to the eastern part of Siberia accompanied by a positive cell over northeastern Europe and Russia. The positive response region again extends into low latitudes in the form of an eastward and poleward moving belt, though it is weaker than that under QBOe. The negative cell appears vertically connected to a negative response in the troposphere over the Aleutian Low in the North Pacific, which is persistently present from 1–30 October to 20 November through 19 December, although it is not significant for 11 October to 9 November. In general, the tropospheric signals are weaker for QBOw than for QBOe. Nevertheless, it is worth noting that, for both QBO phases, the vertical connections of the stratospheric and tropospheric responses are primarily detected around well-known surface pressure anomalies, such as the Aleutian Low, the Canadian High, the Icelandic Low, and the Siberian High.

3.2. Solar Signal in the Planetary Wave Spectrum

[23] In order to examine whether there is a connection between the detected changes in the mean state of geopotential height and wave activity, Figure 4 shows the planetary wave spectrum (Figure 4, left) and the difference between the HS and LS composites for QBOe (Figure 4, middle) and QBOw (Figure 4, right) at 10 hPa for 45°–75°N (Figure 4, top) and at 200 hPa for 40°–60°N (Figure 4, bottom). At 10 hPa, the anomalies in the planetary wave spectrum are clearly different for the two phases of the QBO, especially for periods smaller than 20 days. The same holds at 50 hPa (not shown).

[24] For QBOe, a reduction in planetary wave activity is observed over almost the entire spectrum for the HS-LS condition. The main statistically significant difference is found at wave number 2 with a period of ~8–10 days, which appears to extend also to wave numbers 1 and 3 to some degree. There is also a significant decrease in wave power at wave number 2 with a period of 22.5 days. Differences in other parts of the spectrum are not significant at a confidence level greater than 90%. For QBOw, there is mainly an increase in wave power for periods smaller than 20 days for the HS-LS condition. The main features in this case are significant increases at wave number 3 with periods of 6–6.9 and 10 days. The increase at a period of 10 days only appears when using data from 1958 to 2009, but it is not significant when only the ERA-40 data up to 2001 are used. For that reason, we do not examine this feature any further.

[25] The planetary wave power spectrum at 200 hPa (Figure 4, bottom) shows little significant difference (i.e., at a confidence level of 95%) for QBOe conditions, and the differences that are found do not match with those at 10 hPa. This indicates that there is either a lack of vertical connection in wave activity or it is due to a nonlinear wave-wave interaction that may have caused the characteristics of the planetary waves to change from the lower stratosphere to the upper stratosphere. For QBOw, there is a significant increase in wave power at wave number 2 for a period of 5.6–6 days, which extends toward wave number 1. Other parts of the spectrum show little significant change.

[26] The latitudinal distributions of the changes in planetary wave power identified in Figure 4 are shown in Figures 5 and 6. Figure 5 shows the planetary wave power at 10 hPa for QBOe at wave number 2 with a period of 22.5 days (Figure 5, left) and 8.2–10 days (Figure 5, right), under HS (Figure 5, red line with red shading) and LS (Figure 5, black line with gray shading) conditions. The total wave power is shown (Figure 5a), as well as the power associated with standing (Figure 5b), eastward propagating (Figure 5c), and westward propagating (Figure 5d) waves. This shows that eastward propagating waves contribute most to the differences in both cases, although there are contributions from standing and westward propagating waves as well. At a period of 22.5 days, the reduction in wave power for the HS condition is most significant (i.e., achieving the largest separation between LS and HS) at high latitudes (70°–80°N), while it is most significant at middle latitudes (45°–65°N) for a period of 8.2–10 days. Nevertheless, in both cases the difference is predominantly due to an overall reduction in wave activity for all latitudes, with only a small poleward shift in wave activity at a period of 8.2–10 days.

[27] Figure 6 shows similar plots for QBOw for the total wave power at 10 hPa for wave number 3 with a period of 6–6.9 days (Figure 6, left) and at 200 hPa for wave numbers 1 and 2 with a period of 5.6–6 days. In both cases, the differences are again primarily associated with eastward propagating waves, although westward propagating waves also make a significant contribution at 200 hPa (not shown). At 10 hPa, there is a significant increase in the wave activity for wave number 3 with a period of 6–6.9 days at 45°–65° N, without any noticeable latitudinal shift in wave power. At 200 hPa, for wave numbers 1 and 2 with a period of 5.6–6 days, the increase is statistically significant only on the equatorward side (35°–45°N), and the difference therefore represents an equatorward shift of wave activity. A similar change in wave power is also present at wave number 3 with a period of 5.6–6 days at 500 hPa (not shown). These results imply that under QBOw, high solar activity is associated with stronger planetary wave activity in the stratosphere and an equatorward shifted wave activity in the troposphere.

4. Discussion

4.1. Solar Signal in the Mean Geopotential Height

[28] We confirm previous findings by *Labitzke and van Loon* [1988] that the polar stratospheric response to the 11 year SC is opposite for the two phases of the QBO. We find that this does not only hold for later winter but also for early winter. Under QBOe conditions, the polar response is predominantly positive, while it is mainly negative under QBOw conditions. However, the sign of the early winter response is opposite to the late winter signals found in the lower stratosphere [*Labitzke and van Loon*, 1988; *Lu et al.*, 2009]. In the low-latitude stratosphere, the solar signal consists of a positive response belt for both QBO phases, although it is stronger for QBOe conditions than for QBOw conditions. This signal is stronger at 10 hPa than at 50 hPa, which suggests it originated in the upper stratosphere rather than the lower stratosphere, in agreement with *Gray et al.* [2001a, 2001b], *Gray* [2003], *Lu et al.* [2009], and *Rigby* [2010]. The mechanism responsible for this low-latitude

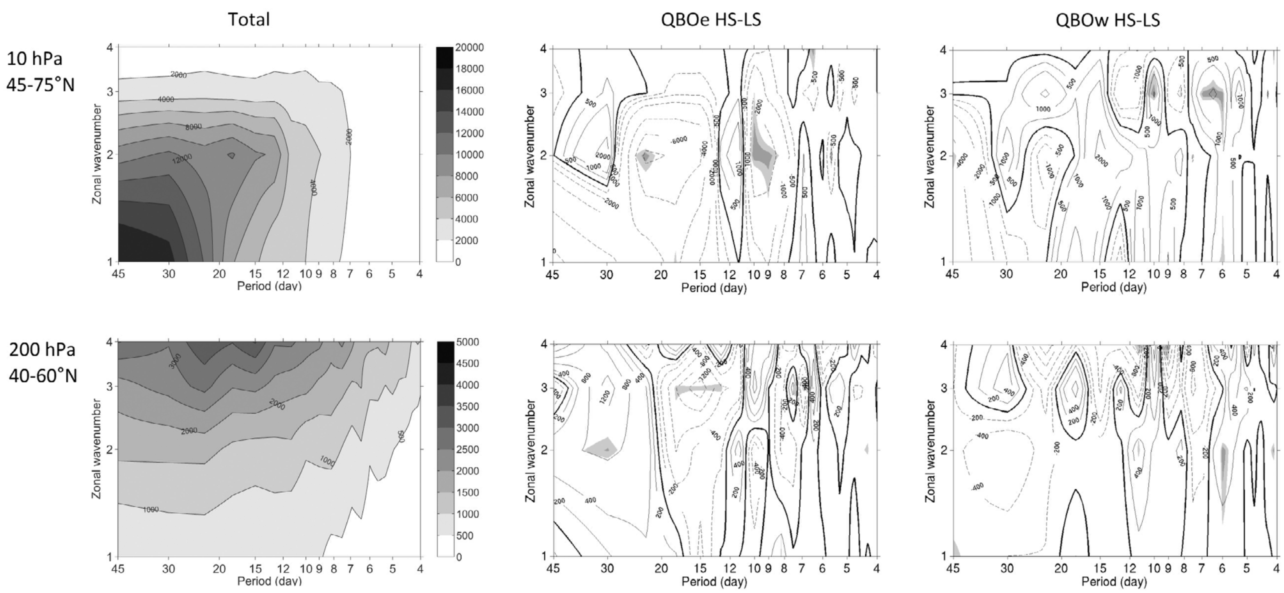

Figure 4. (left) Planetary wave spectrum and the difference between HS and LS for (middle) QBOe and (right) QBOw at (top) 10 hPa for 45°–75°N and (bottom) 200 hPa for 40°–60°N for OND.

response is most likely the direct interaction of solar UV radiation with stratospheric ozone.

[29] A possible mechanism to explain the polar stratospheric solar signals, and their QBO dependence, is schematically illustrated in Figure 7. Under QBOe conditions (Figure 7, left), the polar vortex is relatively weak, and for that reason, it is more easily intruded and disturbed by air from lower latitudes [*Holton and Tan*, 1980, 1982]. The belt of positive response appears to spiral eastward and poleward over time, along with the westerly mean flow. It moves around the negative anomaly over the Atlantic Ocean, until it eventually merges with and reinforces the positive cell over the Canadian High. Thus, the main process involved appears to be the advection of air from lower latitudes into the polar region, which carries the solar-induced positive signal with it (see Figure 7, left).

[30] Under QBOw conditions (Figure 7, right), the polar vortex is relatively strong to start with in early winter [*Lu et al.*, 2008; *Naoe and Shibata*, 2010] and is therefore not easily intruded or disturbed. While again a belt of positive response is present at low latitudes, it is considerably weaker than it is under QBOe, and its poleward movement appears to be blocked over the Eurasian continent. As the polar vortex remains strong and relatively undisturbed by advection of air from lower latitudes, a negative anomaly forms over the polar region. The origin of this anomaly is not clear, but it appears to be distinctly different from the low-latitude response. The negative anomaly eventually gets weaker during 30 November to 29 December. This could be due to planetary wave forcing building up as winter progresses, which is anomalously stronger under HS/QBOw (see Figure 4). This may result in more disturbance of the polar vortex in middle to late winter.

[31] Under both QBO phases, a vertical connection between responses in the high-latitude stratosphere and in the troposphere was detected. Under QBOe, there is a negative cell present during October and November over northwestern Europe and the North Atlantic Ocean, and during QBOw, there is a negative cell over the North Pacific, which are both vertically coherent. Under QBOe, there does not appear to be a time lag between the stratospheric and tropospheric signals in these locations, as would be expected if the tropospheric signals had been caused by a downward propagation of the stratospheric signals. Under QBOw, it is less clear, as the negative cell in the North Pacific is not significant for 11 October to 9 November at 500 hPa, and not for 21 October to 19 November either at 200 hPa. It is therefore possible to interpret the results for QBOw as a lag between the stratospheric and tropospheric responses of ~20 days, with the stratosphere leading. Still, the presence of such a time lag alone is not sufficient to say that the signal originated in the stratosphere [*Plumb and Semeniuk*, 2003]. Moreover, *Nikulin and Lott* [2010] recently found that the downward propagation of stratospheric anomalies occurs only at periods longer than 50 days. This suggests that the signals in response to the 11 year SC that we find formed within the troposphere itself. It is not clear what the mechanism would be, but it does appear that the solar forcing causes a modification of well-known surface pressure anomalies, as the main signals appear over the Aleutian Low (under QBOw) and the Icelandic Low (under QBOe).

[32] The tropospheric signals we find are in general agreement with the results of *Lu et al.* [2009], who showed that the solar signal in zonal mean temperature starts with a negative anomaly in early winter in the troposphere for both QBOe and QBOw conditions [*Lu et al.*, 2009, Figure 6]. The result for QBOw is in agreement with the finding by *Berg et al.* [2007] that significant tropospheric signals occur primarily over the Pacific Ocean. *Woollings et al.* [2010] also showed a strong signal over the Pacific Ocean but, in addition, found a signal in the eastern part of the North Atlantic that was enhanced when open solar flux, rather than

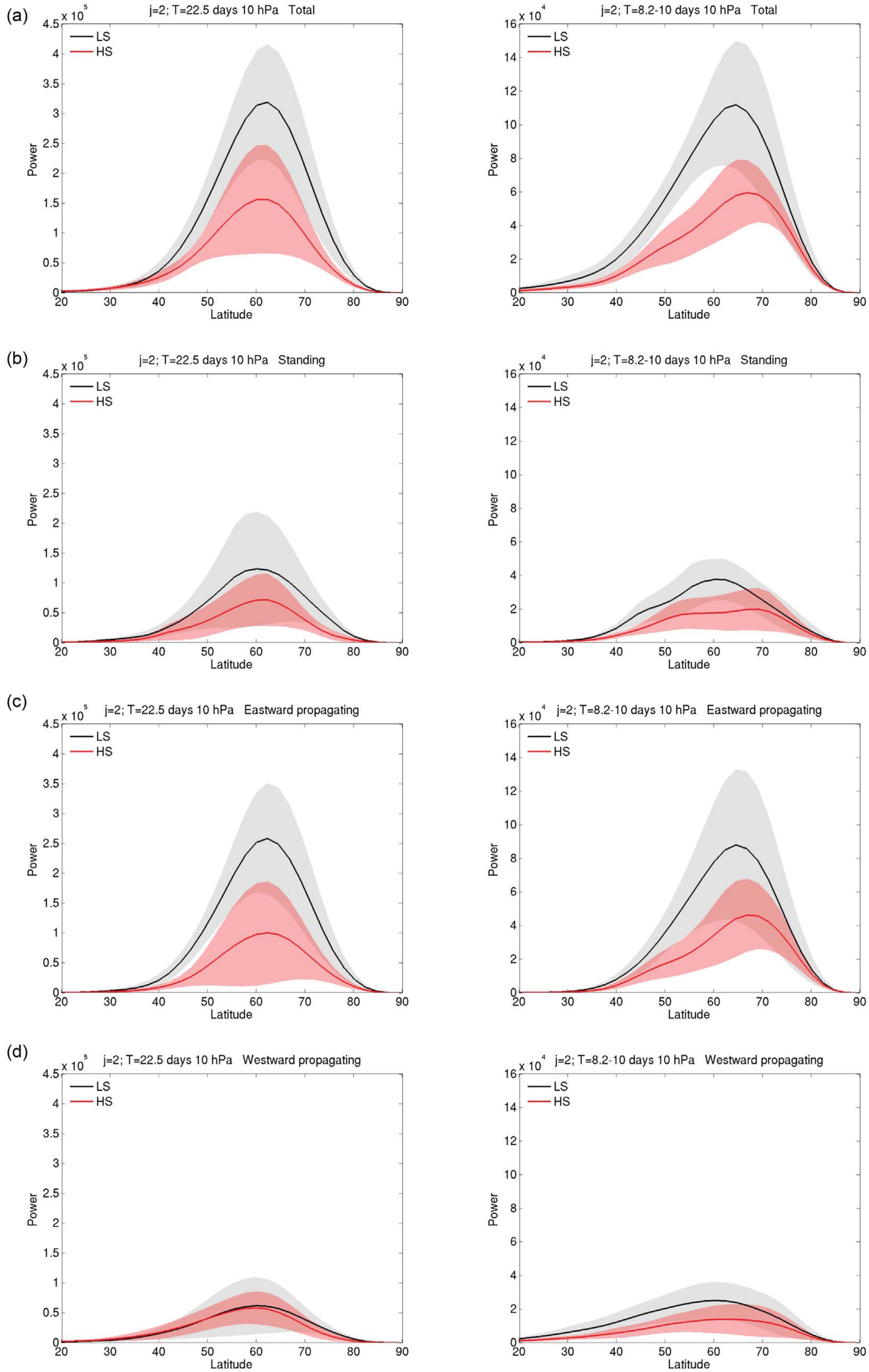

Figure 5. (a–d) Total, standing, eastward propagating, and westward propagating wave power as a function of latitude at wave number 2 and (left) a period of 22.5 days and (right) a period of 8.2–10 days at 10 hPa for HS (red line with red shading) and LS (black line with gray shading) for OND and QBOe. The shading indicates the 95% of confidence interval.

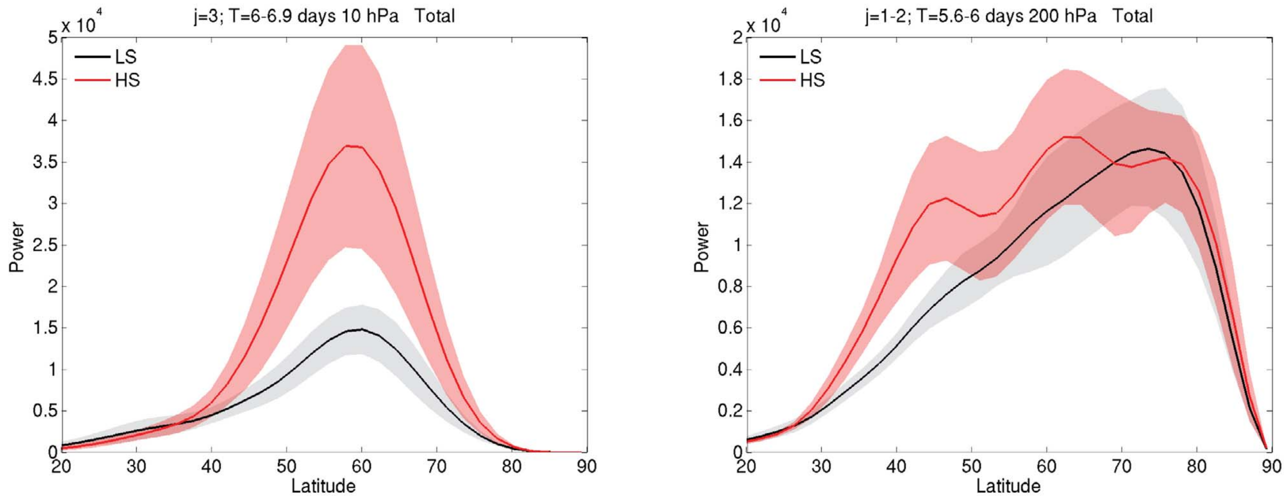

Figure 6. Total wave power as a function of latitude at (left) wave number 3 and a period of 6–6.9 days at 10 hPa and (right) wave numbers 1 and 2 and a period of 5.6–6 days at 200 hPa for HS (red) and LS (black) for OND and QBOw. The shading indicates the 95% of confidence interval.

the F10.7 solar flux, was used to characterize the 11 year SC. This response region corresponds very well with the location of our negative anomaly under QBOe conditions.

[33] The tropospheric signals can also be compared to the changes in blocking in response to the 11 year SC. *Barriopedro et al.* [2008] found that the 11 year SC modulates the preferred locations for blocking occurrence over both the Atlantic and Pacific oceans. High solar activity enhances blocking over the eastern part of the Pacific Ocean, while Atlantic blocking is characterized by a spatially dependent response, confined to either the western (high solar) or eastern (low solar) Atlantic. Again, the preferred locations of these responses are in good agreement with our results.

[34] We thus confirm recent findings that the tropospheric solar signals are strongly regional in character, rather than zonally uniform. The original contribution of this study is that these signals are vertically connected from the troposphere to the stratosphere in the NH early winter and that they are modulated by the QBO. More research is needed to understand how and where the responses are formed initially and why their preferred locations are dependent on the phase of the QBO. Also, the results presented here should be verified in the future, when longer data sets become available. This applies, in particular, to the troposphere, as the magnitude of the stratospheric signals is much larger than the ranges of uncertainty associated with the data as reported in the literature.

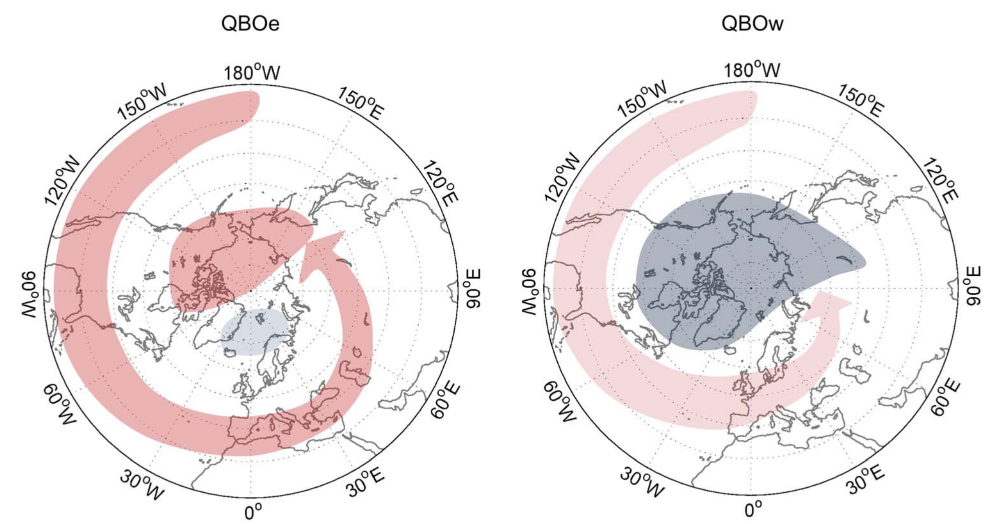

Figure 7. Diagram showing schematically the cause of the different polar stratospheric signal in early winter under QBOe and QBOw conditions, according to our hypothesis. Under QBOe conditions, the low-latitude positive signal is able to enter the relatively weak polar vortex through the advection of low-latitude air. Under QBOw conditions, the poleward movement of low-latitude air is blocked, allowing the negative signal to develop. The figure is adapted from *Rigby* [2010].

4.2. Solar Signal in the Planetary Wave Spectrum

[35] Our results indicate that under QBOe conditions, there is an overall reduction in planetary wave activity at 10 hPa under the HS-LS condition, while this is reversed for QBOw. The significantly stronger wave forcing under LS/QBOe and HS/QBOw conditions is in agreement with results obtained in previous studies regarding changes in the occurrence frequency of SSWs [*Labitzke and van Loon*, 1988], which showed more SSWs occur for LS than HS during QBOe conditions, while more SSWs occur for HS during QBOw.

[36] Under QBOe, the strongest significant change in planetary wave activity is found at 10 hPa. The signal weakens gradually as our analysis moves downward, and it completely disappears at 200 hPa. Little change in planetary wave activity in relation to the 11 year SC is detected in the troposphere. We therefore conclude that the signal at 10 hPa must have originated locally within the stratosphere itself, likely in response to the low-latitude solar UV forcing. This is in agreement with the results from the mean state (see Figure 2).

[37] Under QBOw, a common feature in changes of planetary wave activity is detected in the troposphere and stratosphere. At 200 and 500 hPa, an increase in planetary wave power was found for wave numbers 1–3 with a period of 5.6–6 days, while at 10 and 50 hPa, an increase in planetary wave power was found for wave number 3 with a period of 6–6.9 days. In both cases, the changes were associated primarily with eastward propagating waves. These results suggest that the planetary wave changes in this part of the spectrum are vertically coherent. *Hu and Tung* [2002] suggested that changes in wave number 2 in the stratosphere (at 50 hPa) from November to December are determined by tropospheric forcing. It is possible that the direct influence of changes in tropical lower stratospheric temperatures on the refraction of storm track eddies might be part of the cause, as demonstrated by *Simpson et al.* [2009]. However, further modeling studies are required to fully understand how these midlatitude tropospheric waves are enhanced.

[38] A recent study by *Naoe and Shibata* [2010] on changes in planetary waves associated with the QBO showed that the significant differences in wave activity during early winter (November to December) were associated with wave number 2. They also found little evidence for a poleward shift of wave activity in the lower stratosphere and suggested that the dominant mechanism for the polar winter responses to the QBO may not be through the equatorial winds in the lower stratosphere acting as a waveguide for midlatitude planetary wave propagation. Similarly, our spectral analysis of the QBO-modulated 11 year SC responses shows that the stratospheric response is primarily associated with wave number 2 under QBOe. There is only a slight poleward shift of wave activity under HS/QBOe at wave number 2 with a period of 8.2–10 days, and the effect is stronger at 10 hPa than at 50 hPa. Under QBOw conditions, there is no evidence for a latitudinal shift in planetary wave activity in the stratosphere, although an equatorward shift in wave activity is detected in the troposphere. The dominant mechanism for the early winter responses to the 11 year SC can therefore not be through a waveguide effect of the equatorial winds in the lower or middle stratosphere either.

[39] The lack of a pronounced latitudinal shift in wave activity we find in the stratosphere seems to disagree with *Kodera and Kuroda* [2002], who proposed that more planetary waves are deflected poleward from the upper stratospheric subtropics during solar maximum. This apparent discrepancy may be due to the different altitudes under consideration. Our analysis only goes up to 10 hPa, while *Kodera and Kuroda* [2002] considered altitudes near the stratopause (~1 hPa). The poleward deflection of planetary waves may be stronger there. However, given that the ERA-40 reanalysis becomes less reliable beyond 3 hPa [*Baldwin and Gray*, 2005], changes in wave activity beyond 3 hPa may not be accurately estimated.

[40] Unlike *Soukharev and Labitzke* [2001], *Salby and Callaghan* [2004], *Berg et al.* [2007], and *Tourpali et al.* [2003], we found that the solar signal in planetary wave number 1 is weaker than that in wave numbers 2 and 3. This may be due to the different times of year studied (December–January–February or extended winter compared to OND), or differences in the years included in the analysis and the data source (FUB, NCEP, or model instead of ERA-40). However, we do find some agreement with the results of *Berg et al.* [2007] for wave number 2. They showed an increase in wave number 2 amplitude for HS-LS at 300 hPa, which is consistent with the increase in wave activity we find at 200 hPa for wave number 2 under QBOw conditions. Our results add on to their finding by showing that the increase is associated with periods of 5.6–6 days.

[41] Our results may also be linked to observations in the mesosphere-lower thermosphere (MLT) by *Pancheva et al.* [2008]. They found oscillations with a period of 22–24 days in the zonal and meridional MLT winds after the onset of SSWs in the stratosphere. As solar signals are also affected by SSWs and vice versa [e.g., *Labitzke and van Loon*, 1988; *Cnossen et al.*, 2011], there could be a connection between their observations and our findings at 10 hPa for QBOe, which showed a solar response in planetary wave activity at a period of 22 days.

[42] Our results do not offer a direct insight into why solar signals appear specifically in waves with periods of 5.6–6 days (QBOw, 200 hPa), 6–6.9 days (QBOw, 10 hPa), and 8.2–10 and 22.5 days (QBOe, 10 hPa). However, we can speculate on some possibilities. Numerous studies have found evidence for naturally occurring waves at the periodicities mentioned above. For instance, *Holton et al.* [2001] reported on zonal wind and temperature oscillations in the stratosphere exhibiting 9.5–10 and 5 day periodicities, while *Madden and Julian* [1972], *Madden* [1978], and *Speth and Madden* [1983] all reported on waves with a 5 day periodicity in the lower atmosphere, with strong signatures especially in geopotential height. It may be that variations in solar activity modify the generation of these naturally occurring waves [*Ebel et al.*, 1981]. This could, for instance, take place through changes in convection and humidity [*Tsuda et al.*, 1994], which would be expected to occur if the solar cycle affects the coupling between air, sea, and radiation over the oceans, as suggested by *Meehl et al.* [2003, 2008] and *van Loon et al.* [2007].

[43] Another possibility is that some of the periodicities are of direct solar origin. A number of studies have revealed

a 9 day periodicity in thermospheric density, which has been linked to recurring fast streams of solar wind coming from solar coronal holes distributed roughly 120° apart in longitude [*Thayer et al.*, 2008; *Lei et al.*, 2008; *Mlynczak et al.*, 2008]. Apparently, this configuration is not limited to a specific year or period [*Temmer et al.*, 2007], but quite general, and it explains the periodicity of one-third of the 27 day solar rotation period in the upper atmosphere. Solar coronal holes tend to emit less UV radiation than the rest of the corona as well, which could potentially cause a signal in the upper stratosphere with a 9 day periodicity. Alternatively, the 9 day periodicity may be a subharmonic response of the atmosphere to a 27 day forcing. With this in mind, it is also worth noting that a period of 6.75 days corresponds to one-fourth of a solar rotation period.

[44] Previous studies have reported a periodicity of approximately half the solar rotation period, 13.6 days, in the stratosphere [*Ebel and Bätz*, 1977; *Ebel et al.*, 1981]. Subsequent modeling studies by *Dameris et al.* [1986] and *Ebel et al.* [1988] showed that a weak forcing with that periodicity gives an atmospheric response that exhibits a broad spectrum of oscillation periods, not restricted to the forcing period. They also found that the waves present in the background atmosphere can have a strong influence on the response to a given forcing. These results point toward an important role for nonlinear processes (wave-wave interaction) contributing to the development of the middle atmosphere response to weak external forcing, such as solar forcing.

[45] For none of the above possibilities, it is obvious why the 11 year SC signal should be different for QBOe and QBOw, although, certainly, the background conditions for wave propagation and the naturally occurring waves themselves would be different. Further research is necessary to get a better understanding of the possible origins of the periodicities we have found and their QBO modulation.

5. Conclusions

[46] First, we studied the response to the 11 year solar cycle, modulated by the QBO, on the mean geopotential height in NH early winter. We investigated, in particular, the vertical connection, longitudinal structure, and temporal evolution of the responses. Our main results are the following:

[47] 1. The stratospheric signal is stronger at 10 hPa than at 50 hPa.

[48] 2. A positive response appears to be initialized at low latitudes for both QBO phases and moves eastward and poleward over time, but this signal itself and its poleward propagation is much weaker under QBOw than QBOe conditions.

[49] 3. Under QBOw conditions, the polar stratospheric signal is predominantly negative, and this can be connected to a negative response over the Aleutian Low in the troposphere.

[50] 4. A weaker negative polar stratospheric signal under QBOe conditions can be connected to a negative tropospheric signal over the eastern part of the Icelandic Low.

[51] 5. The vertical connection pattern either changes or becomes weaker from 10 November to 9 December onward when planetary wave activity increases.

[52] In the second part of the paper, we examined the responses of planetary wave activity to the 11 year SC for the same early winter period and using the same QBO phase separation. We found the following:

[53] 1. There is an overall reduction in planetary wave activity in the stratosphere under QBOe and an overall increase of wave activity under QBOw conditions.

[54] 2. In the stratosphere, the most significant change in planetary wave power under QBOe conditions is detected at wave number 2, while it is at wave number 3 under QBOw conditions.

[55] 3. The significant changes in planetary wave activity in the stratosphere are primarily due to an overall decrease (increase) in wave strength under QBOe (QBOw) conditions at middle to high latitudes, while latitudinal shifts in wave activity play a minor role.

[56] 4. Under QBOe conditions, significant changes in planetary wave activity are mostly confined to the stratosphere.

[57] 5. Under QBOw conditions, an increase in planetary wave power at wave numbers 1–3 with a period of 5.6–6.9 days is found in both the stratosphere and troposphere. In the troposphere, the increase occurred primarily at 35°–45°N, representing an equatorward shift of wave activity.

[58] Combining the results from both parts of our analysis, we conclude that the stratospheric response to the 11 year SC is initiated in the upper stratospheric equatorial region, as previously suggested by *Gray et al.* [2001a, 2001b] and *Gray* [2003]. Nevertheless, the poleward propagation of these early winter signals does not take place via changes in the latitudinal distribution of planetary waves as no significant latitudinal shift in planetary wave power is found. The signal is not due to an overall enhanced planetary wave activity either, because the positive signal at 10 hPa is associated with a significantly reduced wave activity under the HS/QBOe condition. Instead, the overall signature detected in the mean state and the planetary waves suggests that the response moves poleward through the advection of low-latitude air. This mechanism is less disturbed under QBOe conditions than under QBOw conditions. Further research is needed to determine how the tropospheric signals might form under different QBO phases. Also, it is critical that atmospheric measurements continue in order to extend the current data sets available for analysis. The statistical significance of our results is limited in part because of the relatively few samples available in some of the conditions (especially QBO/HS), and the analysis should be repeated in the future when longer data sets become available.

[59] **Acknowledgments.** We thank Tony Philips for help with acquiring and managing the ERA-40 and ERA-Interim data. We are also grateful to Drs. Valerio Lucarini and Alessando Dell'Aquila for making the code to perform the Hayashi spectral analysis freely available online and for their help in using the code correctly. Finally, we thank three anonymous reviewers for their constructive comments on the original version of this manuscript.

References

Baldwin, M. P., and L. J. Gray (2005), Tropical stratospheric zonal winds in ECMWF ERA-40 reanalysis, rocketsonde data and rawinsonde data, *Geophys. Res. Lett.*, *32*, L09806, doi:10.1029/2004GL022328.

Barriopedro, D., R. García-Herrera, and R. Huth (2008), Solar modulation of Northern Hemisphere winter blocking, *J. Geophys. Res.*, *113*, D14118, doi:10.1029/2008JD009789.

Berg, P., B. Christiansen, P. Thejll, and N. Arnold (2007), The dynamical response of the middle atmosphere to the tropospheric solar signal, *J. Geophys. Res.*, *112*, D20122, doi:10.1029/2006JD008237.

Cnossen, I., H. Lu, C. J. Bell, L. J. Gray, and M. M. Joshi (2011), Solar signal propagation: The role of gravity waves and stratospheric sudden warmings, *J. Geophys. Res.*, *116*, D02118, doi:10.1029/2010JD014535.

Crooks, S. A., and L. J. Gray (2005), Characterization of the 11-year solar signal using a multiple regression analysis of the ERA-40 dataset, *J. Clim.*, *18*, 996–1015, doi:10.1175/JCLI-3308.1.

Dameris, M., A. Ebel, and H. J. Jakobs (1986), Three-dimensional simulation of quasi-periodic perturbations attributed to solar activity effects in the middle atmosphere, *Ann. Geophys.*, *4*(4), 287–296.

Dee, D. P., and S. Uppala (2009), Variational bias correction of satellite radiance data in the ERA-Interim reanalysis, *Q. J. R. Meteorol. Soc.*, *135*, 1830–1841, doi:10.1002/qj.493.

Dell'Aquila, A., V. Lucarini, P. M. Ruti, and S. Calmanti (2005), Hayashi spectra of the Northern Hemisphere mid-latitude atmospheric variability in the NCEP-NCAR and ECMWF reanalyses, *Clim. Dyn.*, *25*, 639–652, doi:10.1007/s00382-005-0048-x.

Dell'Aquila, A., P. M. Ruti, S. Calmanti, and V. Lucarini (2007), Southern Hemisphere midlatitude atmospheric variability of the NCEP-NCAR and ECMWF reanalyses, *J. Geophys. Res.*, *112*, D08106, doi:10.1029/2006JD007376.

Ebel, A., and W. Bätz (1977), Response of stratospheric circulation at 10 mb to solar activity oscillations resulting from the sun's rotation, *Tellus*, *29*, 41–47, doi:10.1111/j.2153-3490.1977.tb00707.x.

Ebel, A., B. Schwister, and K. Labitzke (1981), Planetary waves and solar activity in the stratosphere between 50 and 10 mbar, *J. Geophys. Res.*, *86*(C10), 9729–9738, doi:10.1029/JC086iC10p09729.

Ebel, A., M. Dameris, and H. J. Jakobs (1988), Modelling of the dynamical response of the middle atmosphere to weak external forcing: Influence of stationary and transient waves, *Ann. Geophys.*, *6*(5), 501–512.

Frame, T. H. A., and L. J. Gray (2010), The 11-yr solar cycle in ERA-40 data: An update to 2008, *J. Clim.*, *23*, 2213–2222, doi:10.1175/2009JCLI3150.1.

Gleisner, H., and P. Thejll (2003), Patterns of tropospheric response to solar variability, *Geophys. Res. Lett.*, *30*(13), 1711, doi:10.1029/2003GL017129.

Gleisner, H., P. Thejll, M. Stendel, E. Kaas, and B. Machenhauer (2005), Solar signals in tropospheric re-analysis data: Comparing NCEP/NCAR and ERA40, *J. Atmos. Sol. Terr. Phys.*, *67*(8–9), 785–791, doi:10.1016/j.jastp.2005.02.001.

Gray, L. J. (2003), The influence of the equatorial upper stratosphere on stratospheric sudden warmings, *Geophys. Res. Lett.*, *30*(4), 1166, doi:10.1029/2002GL016430.

Gray, L. J., E. F. Drysdale, T. J. Dunkerton, and B. N. Lawrence (2001a), Model studies of the interannual variability of the northern-hemisphere stratospheric winter circulation: The role of the quasi-biennial oscillation, *Q. J. R. Meteorol. Soc.*, *127*, 1413–1432, doi:10.1002/qj.49712757416.

Gray, L. J., S. J. Phipps, T. J. Dunkerton, M. P. Baldwin, E. F. Drysdale, and M. R. Allen (2001b), A data study of the influence of the equatorial upper stratosphere on northern-hemisphere stratospheric sudden warmings, *Q. J. R. Meteorol. Soc.*, *127*, 1985–2003, doi:10.1002/qj.49712757607.

Gray, L. J., S. Crooks, C. Pascoe, S. Sparrow, and M. Palmer (2004), Solar and QBO influences on the timing of stratospheric sudden warmings, *J. Atmos. Sci.*, *61*, 2777–2796, doi:10.1175/JAS-3297.1.

Gray, L. J., et al. (2010), Solar influences on climate, *Rev. Geophys.*, *48*, RG4001, doi:10.1029/2009RG000282.

Haigh, J. D. (2003), The effects of solar variability on the Earth's climate, *Philos. Trans. R. Soc. A*, *361*(1802), 95–111.

Haigh, J. D., M. Blackburn, and R. Day (2005), The response of tropospheric circulation to perturbations in lower-stratospheric temperature, *J. Clim.*, *18*, 3672–3685, doi:10.1175/JCLI3472.1.

Hameed, S., and J. N. Lee (2005), A mechanism for sun-climate connection, *Geophys. Res. Lett.*, *32*, L23817, doi:10.1029/2005GL024393.

Hayashi, Y. (1971), A generalized method for resolving disturbances into progressive and retrogressive waves by space Fourier and time crossspectral analysis, *J. Meteorol. Soc. Jpn.*, *49*, 125–128.

Hayashi, Y. (1979), A generalized method for resolving transient disturbances into standing and travelling waves by space-time spectral analysis, *J. Atmos. Sci.*, *36*, 1017–1029.

Holton, J. R., and H. C. Tan (1980), The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb, *J. Atmos. Sci.*, *37*, 2200–2208, doi:10.1175/1520-0469(1980)037<2200:TIOTEQ>2.0.CO;2.

Holton, J. R., and H. C. Tan (1982), The quasi-biennial oscillation in the Northern Hemisphere lower stratosphere, *J. Meteorol. Soc. Jpn.*, *60*, 140–148.

Holton, J. R., M. J. Alexander, and M. T. Boehm (2001), Evidence for short vertical wavelength Kelvin waves in the Dept. of Energy-Atmospheric Radiation Measurement Nauru99 radiosonde data, *J. Geophys. Res.*, *106*, 20,125–20,129, doi:10.1029/2001JD900108.

Hood, L. L. (2004), Effects of solar UV variability on the stratosphere, in *Solar Variability and Its Effects on Climate*, *Geophys. Monogr. Ser.*, vol. 141, edited by J. Pap et al., pp. 283–303, AGU, Washington, D. C.

Hu, Y., and K. K. Tung (2002), Tropospheric and equatorial influences on planetary-wave amplitude in the stratosphere, *Geophys. Res. Lett.*, *29*(2), 1019, doi:10.1029/2001GL013762.

Kodera, K., and Y. Kuroda (2002), Dynamical response to the solar cycle, *J. Geophys. Res.*, *107*(D24), 4749, doi:10.1029/2002JD002224.

Kodera, K., and Y. Kuroda (2005), A possible mechanism of solar modulation of the spatial structure of the North Atlantic Oscillation, *J. Geophys. Res.*, *110*, D02111, doi:10.1029/2004JD005258.

Labitzke, K. (1987), Sunspots, the QBO, and the stratospheric temperature in the north polar-region, *Geophys. Res. Lett.*, *14*(5), 535–537, doi:10.1029/GL014i005p00535.

Labitzke, K. (2005), On the solar cycle-QBO relationship: A summary, *J. Atmos. Sol. Terr. Phys.*, *67*(1–2), 45–54, doi:10.1016/j.jastp.2004.07.016.

Labitzke, K., and H. van Loon (1988), Associations between the 11-year solar-cycle, the QBO and the atmosphere 1. The troposphere and stratosphere in the Northern Hemisphere in winter, *J. Atmos. Terr. Phys.*, *50*(3), 197–206, doi:10.1016/0021-9169(88)90068-2.

Labitzke, K., M. Kunze, and S. Bronnimann (2006), Sunspots, the QBO and the stratosphere in the North Polar Region—20 years later, *Meteorol. Z.*, *15*, 355–363, doi:10.1127/0941-2948/2006/0136.

Lean, J. (2005), Living with a variable sun, *Phys. Today*, *58*(6), 32–38, doi:10.1063/1.1996472.

Lei, J., J. P. Thayer, J. M. Forbes, E. K. Sutton, and R. S. Nerem (2008), Rotating solar coronal holes and periodic modulation of the upper atmosphere, *Geophys. Res. Lett.*, *35*, L10109, doi:10.1029/2008GL033875.

Lockwood, M., R. G. Harrison, T. Woollings, and S. K. Solanki (2010), Are cold winters in Europe associated with low solar activity?, *Environ. Res. Lett.*, *5*, 024001, doi:10.1088/1748-9326/5/2/024001.

Lu, H., M. J. Jarvis, H.-F. Graf, P. C. Young, and R. B. Horne (2007), Atmospheric temperature response to solar irradiance and geomagnetic activity, *J. Geophys. Res.*, *112*, D11109, doi:10.1029/2006JD007864.

Lu, H., M. P. Baldwin, L. J. Gray, and M. J. Jarvis (2008), Decadal-scale changes in the effect of the QBO on the northern stratospheric polar vortex, *J. Geophys. Res.*, *113*, D10114, doi:10.1029/2007JD009647.

Lu, H., L. J. Gray, M. P. Baldwin, and M. J. Jarvis (2009), Life cycle of the QBO-modulated 11-year solar cycle signals in the Northern Hemispheric winter, *Q. J. R. Meteorol. Soc.*, *135*, 1030–1043, doi:10.1002/qj.419.

Lucarini, V., S. Calmanti, S. Dell'Aquila, P. M. Ruti, and A. Speranza (2007), Intercomparison of the northern hemisphere winter mid-latitude atmospheric variability of the IPCC models, *Clim. Dyn.*, *28*, 829–848, doi:10.1007/s00382-006-0213-x.

Madden, R. A. (1978), Further evidence of traveling planetary waves, *J. Atmos. Sci.*, *35*, 1605–1618, doi:10.1175/1520-0469(1978)035<1605:FEOTPW>2.0.CO;2.

Madden, R. A., and P. Julian (1972), Further evidence of global-scale 5-day pressure waves, *J. Atmos. Sci.*, *29*, 1464–1469, doi:10.1175/1520-0469(1972)029<1464:FEOGSD>2.0.CO;2.

Matthes, K., U. Langematz, L. L. Gray, K. Kodera, and K. Labitzke (2004), Improved 11-year solar signal in the Freie Universität Berlin Climate Middle Atmosphere Model (FUB-CMAM), *J. Geophys. Res.*, *109*, D06101, doi:10.1029/2003JD004012.

Matthes, K., Y. Kuroda, K. Kodera, and U. Langematz (2006), Transfer of the solar signal from the stratosphere to the troposphere: Northern winter, *J. Geophys. Res.*, *111*, D06108, doi:10.1029/2005JD006283.

Mechoso, C. R., and D. L. Hartmann (1982), An observational study of travelling planetary waves in the Southern hemisphere, *J. Atmos. Sci.*, *39*, 1921–1935, doi:10.1175/1520-0469(1982)039<1921:AOSOTP>2.0.CO;2.

Meehl, G. A., W. M. Washington, T. M. L. Wigley, J. M. Arblaster, and A. Dai (2003), Solar and greenhouse gas forcing and climate response in the twentieth century, *J. Clim.*, *16*, 426–444, doi:10.1175/1520-0442(2003)016<0426:SAGGFA>2.0.CO;2.

Meehl, G. A., J. M. Arblaster, G. Branstator, and H. van Loon (2008), A coupled air-sea response mechanism to solar forcing in the Pacific region, *J. Clim.*, *21*, 2883–2897, doi:10.1175/2007JCLI1776.1.

Meehl, G. A., J. M. Arblaster, K. Matthes, F. Sassi, and H. van Loon (2009), Amplifying the Pacific Climate System response to a small 11-year solar cycle forcing, *Science*, *325*, 1114–1118, doi:10.1126/science.1172872.

Mlynczak, M. G., F. J. Martin-Torres, C. J. Mertens, B. T. Marshall, R. E. Thompson, J. U. Kozyra, E. E. Remsberg, L. L. Gordley, J. M. Russell III, and T. Woods (2008), Solar–terrestrial coupling evidenced by periodic behavior in geomagnetic indexes and the infrared energy budget of the thermosphere, *Geophys. Res. Lett.*, *35*, L05808, doi:10.1029/2007GL032620.

Naito, Y., and I. Hirota (1997), Interannual variability of the northern winter stratospheric circulation related to the QBO and the solar cycle, *J. Meteorol. Soc. Jpn.*, *75*, 925–937.

Naoe, H., and K. Shibata (2010), Equatorial quasi-biennial oscillation influence on northern winter extratropical circulation, *J. Geophys. Res.*, *115*, D19102, doi:10.1029/2009JD012952.

Nikulin, G., and F. Lott (2010), On the time-scales of the downward propagation and of the tropospheric planetary wave response to the stratospheric circulation, *Ann. Geophys.*, *28*(2), 339–351, doi:10.5194/angeo-28-339-2010.

Pancheva, D., et al. (2008), Planetary waves in coupling the stratosphere and mesosphere during the major stratospheric warming in 2003/2004, *J. Geophys. Res.*, *113*, D12105, doi:10.1029/2007JD009011.

Plumb, R. A., and K. Semeniuk (2003), Downward migration of extratropical zonal wind anomalies, *J. Geophys. Res.*, *108*(D7), 4223, doi:10.1029/2002JD002773.

Rigby, M. H. N. (2010), Northern hemisphere winter stratospheric flow regimes, Ph.D. thesis, 256 pp., Exeter College, Univ. of Oxford, Oxford, U. K.

Salby, M., and P. Callaghan (2004), Evidence of the solar cycle in the general circulation of the stratosphere, *J. Clim.*, *17*, 34–46, doi:10.1175/1520-0442(2004)017<0034:EOTSCI>2.0.CO;2.

Schäfer, J. (1979), A space-time analysis of tropospheric planetary waves in the Northern hemisphere, *J. Atmos. Sci.*, *36*, 1117–1123.

Simmons, A., S. Uppala, D. P. Dee, and S. Kobayashi (2007), ERA-Interim: New ECMWF reanalysis products from 1989 onwards, *ECMWF Newsl.*, *110*, 2025–2035.

Simpson, I. R., M. Blackburn, and J. D. Haigh (2009), The role of eddies in driving the tropospheric response to stratospheric heating perturbations, *J. Atmos. Sci.*, *66*, 1347–1365, doi:10.1175/2008JAS2758.1.

Soukharev, B., and K. Labitzke (2001), The 11-yr SC, the Sun's rotation, and the middle stratosphere in winter. Part II: Response of planetary waves, *J. Atmos. Sol. Terr. Phys.*, *63*(18), 1931–1939, doi:10.1016/S1364-6826(01)00065-7.

Speth, P., and R. A. Madden (1983), Space-time spectral analyses of Northern Hemisphere geopotential heights, *J. Atmos. Sci.*, *40*, 1086–1100, doi:10.1175/1520-0469(1983)040<1086:STSAON>2.0.CO;2.

Temmer, M., B. Vršnak, and A. M. Veronig (2007), Periodic appearance of coronal holes and the related variation of solar wind parameters, *Sol. Phys.*, *241*, 371–383, doi:10.1007/s11207-007-0336-1.

Thayer, J. P., J. Lei, J. M. Forbes, E. K. Sutton, and R. S. Nerem (2008), Thermospheric density oscillations due to periodic solar wind high-speed streams, *J. Geophys. Res.*, *113*, A06307, doi:10.1029/2008JA013190.

Tourpali, K., C. J. E. Schuurmans, R. van Dorland, B. Steil, and C. Brühl (2003), Stratospheric and tropospheric response to enhanced solar UV radiation: A model study, *Geophys. Res. Lett.*, *30*(5), 1231, doi:10.1029/2002GL016650.

Tsuda, T., Y. Murayama, H. Wiryosumarto, S. W. B. Harijono, and S. Kato (1994), Radiosonde observations of equatorial atmosphere dynamics over Indonesia 1. Equatorial waves and diurnal tides, *J. Geophys. Res.*, *99*(D5), 10,491–10,505, doi:10.1029/94JD00355.

Uppala, S. M., et al. (2005), The ERA-40 reanalysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012, doi:10.1256/qj.04.176.

van Loon, H., G. A. Meehl, and D. J. Shea (2007), Coupled air-sea response to solar forcing in the Pacific region during northern winter, *J. Geophys. Res.*, *112*, D02108, doi:10.1029/2006JD007378.

Woollings, T., M. Lockwood, G. Masato, C. Bell, and L. Gray (2010), Enhanced signature of solar variability in Eurasian winter climate, *Geophys. Res. Lett.*, *37*, L20805, doi:10.1029/2010GL044601.

I. Cnossen, National Center for Atmospheric Research, 3080 Center Green Dr., Boulder, CO 80301, USA. (icnossen@ucar.edu)

H. Lu, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK.