QBO modulation of traveling planetary waves during northern winter

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[1] This study analyzes geopotential height data from the ERA-40 and ERA-Interim reanalyses for the period of 1958–2009 to provide some new insights on the stratospheric Quasi-Biennial Oscillation (QBO) modulation of traveling planetary waves during Northern Hemisphere (NH) winter. In the stratosphere, the zonal wave number 1–3 waves with periods of 22.5–30 days and 45–60 days are found to be significantly stronger at midlatitudes when the QBO at 50 hPa is in its westerly phase than when it is in its easterly phase. The modulation is stronger for eastward propagating and standing waves and weaker for westward propagating waves. A QBO modulation of 11–13 day planetary waves is also found but the effect is dominated by post-satellite data. In the troposphere, significant QBO modulation is only detected in westward propagating waves at zonal wave number 2 with periods of 22.5–30 days in early winter (Oct-Dec). Consistent results in the stratosphere are obtained using the temperature data from SABER/TIMED. The SABER data also show that the QBO effect on the eastward propagating 23-day waves extends into the mesosphere (∼70 km) for wave number 1 and only up to the stratopause (∼45 km) for wave numbers 2 and 3. We suggest that the 22.5–30 day planetary waves are secondary waves generated by a nonlinear coupling between zonal-mean intraseasonal oscillations (ISO) and the well-known 16-day planetary waves. The QBO modulation of those planetary waves is due to a QBO-ISO interaction. Further studies are needed to prove this hypothesis.

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1. Introduction

[2] The relationship between the inter-annual variation of the winter stratospheric polar vortex and the quasi-biennial oscillation (QBO) has been studied since the 1980s. *Holton and Tan* [1980] examined 16 years of Northern Hemispheric (NH) geopotential height data and showed that the monthly mean strength of the polar vortex up to 10 hPa was positively correlated with the equatorial zonal wind at 50 hPa. Namely, the vortex was weaker, warmer, and more disturbed during winters when the QBO was in its easterly phase (QBOe) than in its westerly phase (QBOw). This tendency was also seen in the incidence of major stratospheric sudden warmings with more events occurring under QBOe than under QBOw [*Labitzke*, 1982; *Dunkerton et al.*, 1988]. Later studies confirmed the existence of the Holton-Tan effect up to 1 hPa, although the significance of the late winter signature was much reduced when more data were included [*Dunkerton and Baldwin*, 1991; *Naito and Hirota*, 1997; *Lu et al.*, 2008].

[3] It is important to explain the remote influence of the QBO on winter polar vortex. One possible mechanism involves the upward propagation of quasi-stationary planetary waves that are known to predominantly regulate the middle atmospheric circulation during NH winter [*Andrews et al.*, 1987]. Based on theoretical speculation that the critical layer may reflect quasi-stationary planetary waves [*Charney and Drazin*, 1961], *Holton and Tan* [1980] suggested that the QBO may affect the amplitude of the quasi-stationary planetary waves at mid- a high latitudes by changing the position of the zero-wind line in the low latitude stratosphere, and consequently altering the width of the extratropical waveguide. Under the QBOe condition, the equatorial waveguide shifts more toward the NH subtropics. More planetary waves are then deflected polewards, resulting in a more disturbed polar vortex and higher polar temperatures. However, observational studies devoted to understand to what extent the QBO modulates the planetary waves in the NH winter have given inconclusive results so far.

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[4] *Holton and Tan* [1980] found that, in early winter (November to December), the amplitude of zonal wave number 1 at 50 hPa and poleward of 40°N is nearly 40% stronger for QBOe than for QBOw conditions. In late winter (January to March), the amplitude of zonal wave number 2 is nearly 60% larger for QBOw than for QBOe conditions. With only 4 additional years of data added to the analysis, a follow-on attempt by *Holton and Tan* [1982] however found that the difference in the Eliassen-Palm (EP) flux between the two QBO phases was not statistically significant.

[5] *Dunkerton and Baldwin* [1991] used 25 years of National Meteorological Center data for the period of 1964–1988 to study the role of planetary waves in the link between the QBO and the polar vortex. They found that the weaker polar vortex under QBOe (defined by the equatorial zonal wind at 40 hPa rather than at 50 hPa) was indeed associated with stronger upward EP-flux at high latitude. However, only marginal and statistically insignificant differences were found in the number of planetary wave events and the difference in wave amplitude between the two QBO phases was rather small.

[6] Based on geopotential height data of NCEP reanalysis from 1952 to 2001, *Hu and Tung* [2002] extended the analysis of *Holton and Tan* [1980] to the period of 1952–2001. They found that the wave number 1 waves at 50 hPa and poleward of 40°N were significantly stronger for QBOe than for QBOw in early winter while the difference in wave number 2 is not statistically significant in either early or late winter. They consequently suggested that the changes in wave number 2 in the stratosphere are determined by tropospheric forcing and the QBO has little effect on those waves. By using NCEP reanalysis data for 1958–2002, *Ruzmaikin et al.* [2005] also found that the QBO modulation of wave number 1 waves estimated from the vertical EP-flux F_z at 60°N was significantly stronger under QBOe than under QBOw in early winter. In late winter, the F_z of wave number 2 was significantly stronger under QBOw than QBOe. Though in general agreement with earlier findings of *Holton and Tan* [1980], the magnitudes of the differences in wave amplitudes were considerably smaller.

[7] Using combined data from ERA-40 and ERA-Interim reanalyses from 1980 to 2004, a recent study by *Naoe and Shibata* [2010] showed that planetary wave activity is generally larger under QBOe than QBOw, which is consistent with other studies on the QBO modulation of quasi-stationary planetary waves. *Naoe and Shibata* [2010] also showed that the wave number 2 in eddy heat flux at 30–60°N was significantly stronger under QBOw than under QBOe in November to December. In January to February, zonal wave number 1 was also significantly stronger under QBOw than under QBOe for the same latitude band. Similar results were obtained by *Hitchman and Huesmann* [2009]. However, it remains to be understood to what extent the QBO modulation of the planetary waves at midlatitudes is linked to the wave breaking near the polar vortex.

[8] In addition, the 11-year solar cycle has also been found to affect the NH late-winter QBO-vortex coupling [*Labitzke and van Loon*, 1988]. *Lu et al.* [2008] found that the extra-tropical stratospheric QBO signals were substantially stronger in 1958–1976 than in 1977–1997. *Anstey et al.* [2010] suggested that the decadal variation of the QBO influence on the polar vortex is affected by the seasonal alignment of QBO phase transitions. Nevertheless, the cause of the low frequency variability in the QBO-vortex coupling remains largely unknown.

[9] The effect of the QBO phase on the winter polar vortex and the planetary waves has also been studied by model simulations. Studies based on mechanistic models have generally found that the polar vortex is sensitive to the tropical and subtropical wind state for an intermediate range of wave amplitudes, whereas no such sensitivity exists when the amplitudes are either very large or very small [*Holton and Austin*, 1991; *Chen*, 1996; *O'Sullivan*, 1997]. *Hamilton* [1998] imposed a QBO in the lower stratosphere and found that planetary waves could penetrate across the equator under QBOw near and above 10 hPa, while the waves were restricted to latitudes poleward of ~10°N under QBOe. The upward EP-flux in the high latitude upper troposphere was stronger under QBOe than under QBOw. By varying the altitude of an imposed tropical wind perturbation, *Gray et al.* [2001, 2003] found that the extratropical NH is very sensitive to the equatorial forcing imposed at 10 hPa and above, suggesting that the equatorial waveguide plays an important role in the upper stratosphere. *Pascoe et al.* [2006] found that perturbations to the lower equatorial stratosphere mainly influence the extratropical circulation in early winter while a significant late winter response could only be detected when a QBO was imposed well into the mesosphere. *Naito and Yoden* [2006] imposed idealized zonal momentum forcing at the equator of the stratosphere to mimic the effect of the QBO in a simple mechanistic model, and found that the upward EP-flux in the mid-latitude (30–60°N) stratosphere and troposphere, as well as the equatorward flux just above the tropopause, are significantly larger under QBOw than under QBOe.

[10] An analysis of EP-fluxes by *Calvo et al.* [2007] in simulations with MAECHAM5, which includes a self-generated QBO, suggested an enhancement of upward wave propagation at mid- and high latitudes up to 10 hPa and subsequent equatorward wave refraction under QBOw conditions. Above 10 hPa, the upward propagation diminished, resulting in an intensified polar vortex. Under QBOe conditions, the upward wave propagation at high latitudes was enhanced up to the stratopause, resulting in a weaker polar vortex compared to its climatological condition. Thus, the modeling results of both *Naito and Yoden* [2006] and *Calvo et al.* [2007] support the hypothesis that the extratropical QBO signature occurs through a QBO modulation of the planetary wave propagation as a change in the zonal-mean winds in the tropics modifying the effective waveguide, although these two studies differ in terms of the active region of wave refraction/breaking. In contrast, based on the MRI-CCM that also self-generates the QBO, *Naoe and Shibata* [2010] found that their EP-flux diagnostics do not show any detectable poleward or equator-ward propagation of the waves in the midlatitude lower stratosphere.

[11] In addition to the large amplitude quasi-stationary planetary waves, traveling planetary waves are also part of the natural mode of variability of the Earth's atmosphere and can be forced by irregular thermal or mechanical forcing in the lower atmosphere and/or generated by variability of the quasi-stationary planetary waves [*Salby*, 1984; *Smith*, 1985]. Up-to-date, few studies have been carried out to investigate a possible QBO modulation of traveling planetary waves.

Based on NCEP reanalysis data for the period of 1980–2000, *Miyoshi and Hirooka* [2003] found that the amplitude of 5-day traveling waves in the midlatitude stratosphere is larger when the vertical shear of the equatorial zonal winds is negative than when the wind shear is positive. As their vertical shear was calculated between 70 and 10 hPa, a negative vertical shear value would typically imply that the QBO in the lower stratosphere is in its westerly phase while the QBO at ~10 hPa is in its easterly phase. Thus, if the QBO is defined as the zonal wind anomaly at the equatorial lower stratosphere, their results suggest that the 5-day wave amplitude is larger under QBOw than under QBOe. A similar QBO modulating effect was recently found by *Pancheva et al.* [2010] based on the 5-day waves derived from SABER/TIMED temperatures for the time period of January 2002–December 2007. However, these studies were based on limited data and the statistical significance of their results remains to be assessed. The lack of studies on the QBO modulation of traveling planetary waves prevents a proper attribution of the contributions of the broader spectrum of planetary wave toward the total EP-flux. As a result, the relative importance of quasi-stationary and traveling planetary waves in the link between the QBO and winter polar vortex remains largely unknown.

[12] The main objective of this study is to understand how the QBO affects the hemispheric and vertical structure of traveling planetary waves during NH winter. The principal framework through which we attempt to achieve this goal is through a detailed examination of the broader spectrum of planetary waves in both the wave number and frequency domain. A space-time spectral analysis is applied to NH geopotential height data from the ERA-40 and ERA-Interim reanalyses covering the period of January 1958 to December 2009. This diagnostic method provides us a means to examine the wave numbers as well as the periodicities at a range of heights and latitudes, so that some insight may be gained into the processes that either originate or modify the strength and/or propagation of the waves due to a possible QBO modulation. With the benefit of an extended observational record, it allows us to obtain robust statistics and to reduce possible contamination induced by decadal-scale variations in the Holton-Tan effect [*Lu et al.*, 2008; *Anstey et al.*, 2010]. As an additional confirmation, we utilize temperature data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite to investigate the vertical extent of the identified QBO modulation.

2. Data and Methods

[13] We used the 6-hourly geopotential height field at 2.25° × 2.25° spatial resolution from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim data [*Dee and Uppala*, 2009; *Simmons et al.*, 2007] for 1989–2009, backward extended with ECMWF ERA-40 reanalysis [*Uppala et al.*, 2005] for 1958–1988. 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. It also means that data from the pre-satellite era have been included, which are known to be less reliable in the upper stratosphere. Nevertheless, qualitatively similar results can be obtained either from the full length of ERA-40 (Jan. 1958-Sep. 2001) or from ERA-Interim (Jan. 1989-Dec. 2009).

[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 [e.g., *Holton and Tan*, 1980; *Hu and Tung*, 2002; *Lu et al.*, 2008; *Naoe and Shibata*, 2010]. We defined the QBOw or QBOe state according to the zonal mean zonal wind anomalies averaged over the winter months being greater or smaller than ± 2 m s^{-1}. Transitional winters during which the absolute values of the zonal wind were smaller than this threshold value were excluded. Similar results can be obtained with any threshold value in the range of ± 0–3 m s^{-1}.

[15] In order to distinguish the relative contributions of traveling and standing waves to the total planetary wave variability, the space-time cross-spectral decomposition method of *Hayashi* [1971, 1979] was applied to the 6-hourly geopotential height data. For a given latitude range, the method expresses the disturbance in geopotential height as a function of longitude and time and decomposes this into westward, eastward and standing waves using a Fourier expansion. It is assumed that the standing wave component corresponds to the part of the spectrum that consists of coherent eastward and westward moving components of equal amplitude while the incoherent part of the spectrum represents traveling waves. Note that the standing wave extracted from the Hayashi spectral analysis represents the wave produced by two waves traveling zonally in opposite directions with the same period, amplitude and zonal structure. They therefore only represent a subset of the quasi-stationary waves in the atmosphere. Further description of the Hayashi analysis can be found in the Appendix of *Mechoso and Hartmann* [1982] and more recently in *Lucarini et al.* [2007].

[16] The Hayashi analysis technique has been used previously to study the climatological behavior as well as the interannual and intraseasonal variability of planetary waves in both observational data and GCM simulations [*Hayashi and Golder*, 1977; *Mechoso and Hartmann*, 1982; *Hirota and Hirooka*, 1984; *Hirooka and Hirota*, 1985; *May*, 1999; *Dell'Aquila et al.*, 2005; *Lucarini et al.*, 2007]. The same method was recently applied by *Cnossen and Lu* [2011] to study the vertical connection of the QBO-modulated 11-year solar cycle signature in NH early winter. Similar to *Cnossen and Lu* [2011], here we have followed *Lucarini et al.* [2007] in multiplying the obtained spectra by $k_j \omega_m \tau / 2\pi$, where $k_j = 2\pi j$, $\omega_\mathrm{m} = 2\pi m/\tau$ where j is the wave number index, m is a frequency index, and τ is the length of the time segment that is used to extract the waves. The obtained power spectrum is in units of m^2. Such a scaling is mainly used to allow the high frequency spectra being plotted more clearly on a logarithmic scale.

[17] The meridional and zonal structure of the difference in geopotential height as well as the difference in the zonal mean wave power for wave numbers 1 to 4 and a range of wave frequencies between the two QBO phases were studied for the extended winter period (Oct-Mar), and for early (Oct-Dec) and late (Jan-Mar) winter. The analysis was applied to the 6-hourly geopotential height data at six different pressure levels, of which three were in the stratosphere (5, 10 and 50 hPa) and the other three were in the troposphere (200, 500

and 925 hPa). This allows us to trace the vertical structure of the QBO modulation on planetary wave propagation.

[18] Composite analyses, in which the geopotential height data and the power of traveling as well as standing planetary waves were separated into QBOw and QBOe conditions, were done at each pressure level. For a given pressure level, the Hayashi spectra were first calculated for area-weighted averages of the geopotential height over 20° wide latitude segments from the equator toward the North Pole. Differences in the power spectra between the QBOw and QBOe conditions were then taken and the significance was tested using a Student's *t*-test. This allowed us to detect the latitudes that showed the most significant changes. To further test the robustness of the signals, a bootstrap technique was also used to assess the uncertainty estimated by Student *t*-test. We performed 10,000 bootstrap re-samplings using sampling with replacement. That is: suppose that we have a total N years of data of which N_e are QBOe years and N_w are QBOw years. A synthetic re-sampling, constructing randomly N_e and N_w years of data, was performed and the composite difference between the two groups of data was computed. The 90% and 95% percent confidence levels were then computed from the distribution of the composite differences of 10,000 re-sampling cases. The actual composite difference estimated from the true QBO phases is regarded as statistically significant if it is greater (for positive differences) or smaller (for negative differences) than the values associated with the 90% and 95% confidence levels. As the two testing methods produce nearly identical results for our pioneer cases at 10 hPa, the results based on Student's *t*-test are used for the rest and consequently reported here. On the basis of those results, the latitude bands with the largest significant changes were aggregated in a single latitude band for ease of reporting.

[19] The Hayashi spectra were also calculated for each individual latitude (with a 2.25° interval) to investigate the latitudinal distribution of the planetary waves in those subdomains of the spectrum that showed a significant QBO modulation. This allowed us to investigate whether westward propagating, eastward propagating or standing waves are primarily responsible for the detected differences. In addition, differences were taken for a sequence of 30-day mean geopotential height with a 10 day forward moving step size. The overlap between previous and current mean samples includes the sub-monthly variation of the responses, allowing us to investigate the transient behavior of the responses in the mean field.

[20] The measurements from the SABER instrument [*Russell et al.*, 1999] on the TIMED satellite have provided global kinetic temperature data from the lower stratosphere to the lower thermosphere since 7 December 2001. SABER temperature data were not assimilated into either ERA-40 or ERA-Interim, and thus provide an independent check of the results detected from the ERA reanalyses. The latest Version 1.07 of the SABER/TIMED temperatures (downloaded from http://saber.gats-inc.com) for the period of January 2002 to December 2009 was used here to study the temporal variability and vertical structure of the QBO-modulated planetary wave activity. The data set covers the vertical range from 20 to 120 km and was averaged into 5 km altitude and 10° latitude bins. The lack of continuous measurements at latitudes greater than 50° prevents the wave amplitude to be estimated there.

[21] To add additional confidence to the results, a different diagnostic method was employed for the SABER data than was used for the ERA reanalyses. To reduce the effect of satellite sampling uniformity, the waves (tides and planetary waves) in SABER temperatures were derived by a linear two-dimensional (time-longitude) least squares fitting method that was described in detail by *Pancheva et al.* [2009]. As satellite sampling processes through local time, the aliasing effects are expected to decrease significantly until all waves are fully sampled. That is: all local times are sampled at all longitudes. Because it takes SABER/TIMED 60 days to sample 24 h in local time by combining ascending and descending data together, the time segment used for performing the least squares fitting has to be 60 days.

[22] To minimize the aliasing between tides and planetary waves, all the waves with zonal wave number up to 3 (for planetary waves) or 4 (for tides) were simultaneously extracted from the data [*Pancheva et al.*, 2009]. Zonally symmetric (zero zonal wave number, or s = 0) oscillations were also included to account for the variability of the zonal mean temperature field.

[23] In principle, any wave with a periodicity smaller than 30-days can be fitted within the 60-day time segment. We have chosen to include only the well-known planetary wave normal modes with periods near 5, 10 and 16 days in the fitting procedure. The 23-day waves were also included as those waves have been observed regularly in the winter stratosphere and mesosphere [*Mukhtarov et al.*, 2010; *Pancheva et al.*, 2009]. The rest of variability in the daily temperature data were regarded as noise and treated as a residual term during the fitting.

[24] At a given altitude and latitude, the daily values of the wave amplitudes and phases were obtained by using a 60-day window which steps forward in time at 1-day intervals. The fitting procedure was applied to the entire period of Jan. 2002-Dec. 2009 in order to obtain the temporal evolution of the wave characteristics. The daily wave amplitudes were then averaged for each calendar month to get the monthly mean.

[25] To quantify the average magnitude of the QBO modulation of the identified planetary waves, a least square fitting procedure that is similar to *Huang et al.* [2006a] was applied to the monthly mean wave amplitudes extracted from SABER temperatures. In general, the planetary waves under consideration amplify in the winter months only; because of this regularity we have to assume that the averaged QBO period is 24 months instead of 28 months in order to study the QBO variation in the planetary waves. Fortunately, this is suitable for the SABER data period of Jan. 2002 to Dec. 2009 when the periodicity of the QBO was indeed close to 24 months. With the pre-defined modulating periodicity/frequency, applying the least square fitting procedure to the monthly wave time series allows us to calculate the mean amplitude and phase of the QBO variation in the planetary wave under consideration. Knowing all characteristics (period, amplitude and phase) of the QBO, time-varying QBO amplitudes associated with the given planetary wave can then be reconstructed. This method not only provides an approximate estimation of the mean amplitude of the QBO

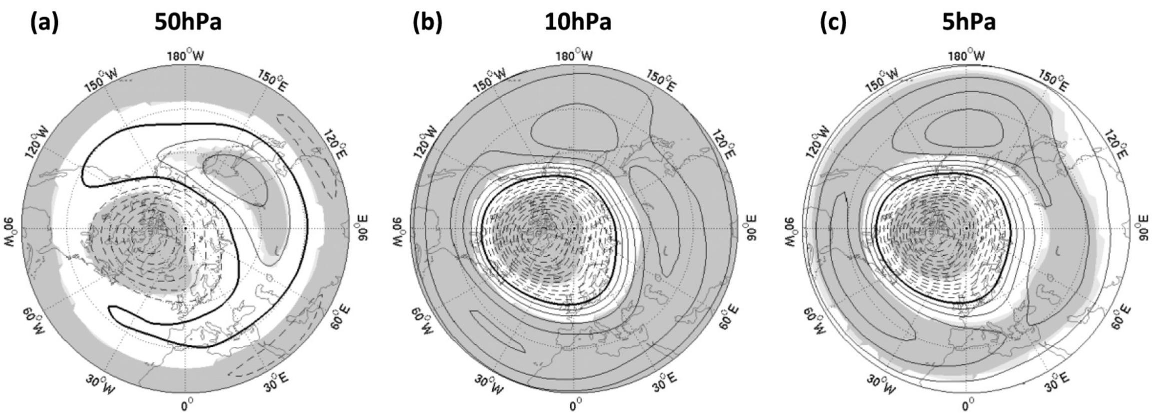

Figure 1. QBO composite difference (QBOw - QBOe) of the geopotential height (Z, in units of meter) averaged over the extended NH winter period (October to March) at (a) 50 hPa, (b) 10 hPa and (c) 5 hPa. The solid (dashed) contours represent positive (negative) difference and the contour interval is 20 m. The light (dark) shadings indicate statistical significance at the 90% (95%) confidence level.

modulation of the waves, but also allows a closer inspection of the vertical structure of the modulation.

3. Results

3.1. QBO Signature in the Geopotential Height From ERA-Reanalyses

[26] Figure 1 shows the composite differences in the October to March mean NH geopotential height between the two QBO phases ($Z_{\text{QBOw-QBOe}}$) at 50, 10, and 5 hPa. In general, the $Z_{\text{QBOw-QBOe}}$ fields at all three stratospheric pressure levels are dominated by a "seesaw" oscillation between the pole and midlatitudes, suggesting that geopotential heights are lower in the polar region and higher at midlatitudes under QBOw than under QBOe. This is consistent with earlier findings [*Holton and Tan*, 1980; *Ruzmaikin et al.*, 2005]. At 50 hPa, an influence of wave number 1 that is marked by positive $Z_{\text{QBOw-QBOe}}$ in Siberia and negative $Z_{\text{QBOw-QBOe}}$ in Greenland and northern Canada is clearly evident. At 5 and 10 hPa, the associated positive center is shifted eastward and coincides with the Aleutian High (~180°W). In addition, planetary scale disturbances by wave numbers 1 and 2 are also visible, characterized by larger values of $Z_{\text{QBOw-QBOe}}$ over the Pacific and Atlantic Ocean basins. Overall, the most significant difference is found at 10 hPa. Above and below this pressure level, the area covered by the confidence level above 95% reduces and it becomes much weaker in the troposphere (not shown).

[27] When the same analysis is applied to a sequence of overlapping 30-day moving windows (not shown), similar disturbances associated with zonally symmetric oscillations and planetary wave number 1 and 2 waves remain robust from October to March, and a wave number 3 pattern also becomes visible (not shown). However, in middle winter (Dec-Feb), the significant parts of the 30-day geopotential height differences ($Z_{\text{QBOw-QBOe}}$) are up to 2.5 times larger than those shown in Figure 1. The largest difference is associated with the positive $Z_{\text{QBOw-QBOe}}$ at midlatitude while only up to 20% increase was found in the negative differences at high latitude. In addition, the wave number 1 and 2 patterns at midlatitudes tend to move around longitudinally with time. In particular, an eastward movement is most evident for the wave number 2 pattern. This implies that, in addition to quasi-stationary planetary waves, traveling planetary waves may also play a role. The question is: to what extent and at what frequency are the patterns shown in Figure 1 linked to the changes of traveling planetary waves that are anomalously enhanced by the QBO?

[28] Figure 2 shows the power spectrum of the total planetary waves (left) and the difference between the two QBO phases (QBOw-QBOe) composites (right) at 5, 10 and 50 hPa (top to bottom), all averaged for 30–65°N and for extended winter months (Oct-Mar). No significant differences were observed for other latitudes bands. The identified 30–65°N latitude band coincides with the stratospheric surf zone where wave activity is the largest. In general, the spectrum of the total planetary waves tends to peak at zonal wave number 2 with periods of 30, 20–25, 15–16, and 9–10 days, reflecting a dominant role of those waves in the stratosphere. A peak for the well-known 5-day waves does not show up as one of the peaks, probably because 5-day waves are generally featured in NH summer but weak in NH winter [*Hirota and Hirooka*, 1984; *Miyoshi and Hirooka*, 2003]. While the magnitude of the total wave power reduces from 5 hPa to 50 hPa, the overall distribution of the spectral power and the peak periodicities remain very similar at all three pressure levels.

[29] Figure 2 (right) shows that, at all the three stratospheric pressure levels, the difference in wave power spectra is generally positive, implying stronger wave activity is associated with QBOw than with QBOe at 30–65°N. For all the three pressure levels, significant differences are found at two or three frequency regimes with the most statistically significant difference at wave number 1 and 2 with periods of ~22.5–30 days. A similar effect appears to extend to wave number 3 at 5 and 10 hPa, at which the 36-day periodicity for wave number 1 is also included. The second most significant increase in wave power is found at wave number 2 with periods of 45–60 days, again at all the three pressure levels. Significant increases in wave power at wave number 2 and 3 with periods of 11–13 days are also detected at 10 hPa. However, those differences are only significant at the 90%

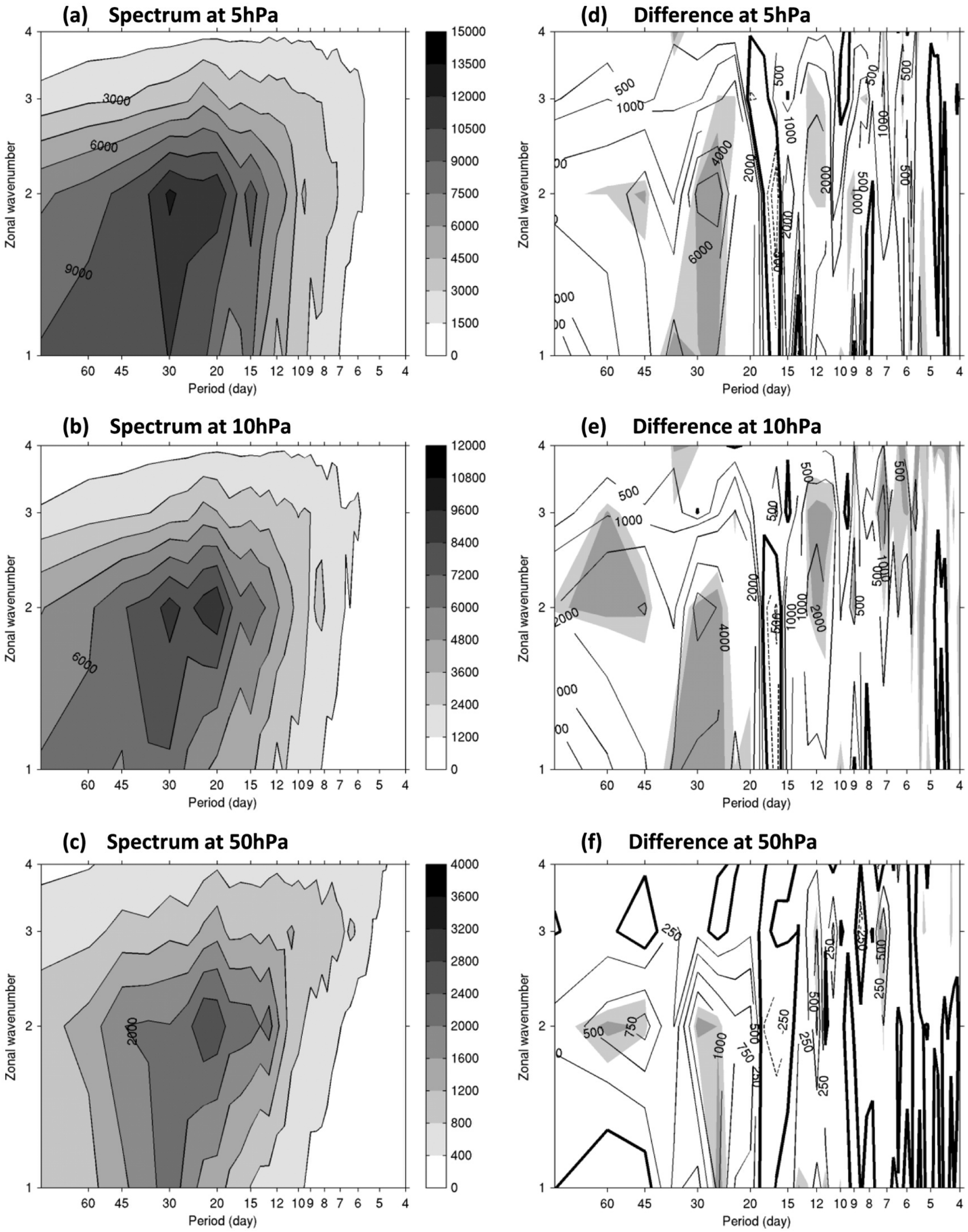

Figure 2. (a, b, and c) Planetary wave spectral power (in units of m^2) as a function of periodicity (*x* axis, in days) and zonal wave numbers 1 to 4 (*y* axis) averaged over 30–65°N and October to March and (d, e, and f) the spectral differences between QBOw and QBOe at 5 hPa (∼43 km), 10 hPa (∼32 km) and 50 hPa (∼21 km). The lines and shadings in the difference plots (Figures 2d, 2e, and 2f) are defined in the same way as in Figure 1.

confidence level at 5 hPa and not significant at a confidence level greater than 90% at 50 hPa.

[30] Figure 3 shows the relative contributions of westward propagating, eastward propagating and standing waves to the total wave power differences for the three stratospheric pressure levels considered by Figure 2. The significant differences in the wave power at 22.5–30 days are detected consistently for all three types of waves and for all three pressure levels. It is most significant at 10 hPa and predominantly at wave number 2. The contribution from westward propagating waves is mainly associated with wave numbers 1 and 2 at 10 and 5 hPa, while the differences in eastward and

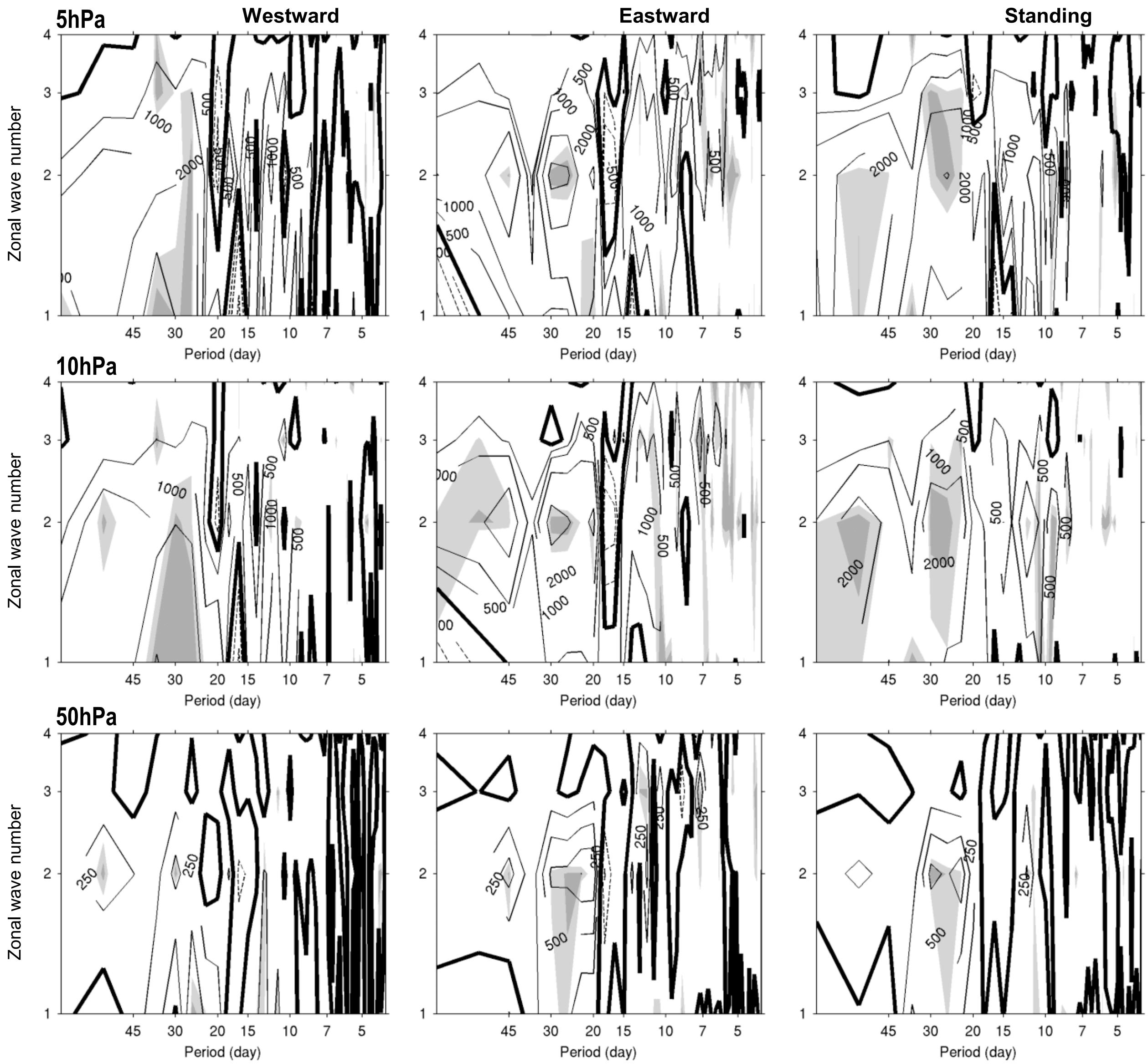

Figure 3. Power spectral differences (in units of m^2) between QBOw and QBOe at (top to bottom) 5 hPa, 10 hPa and 50 hPa for (left to right) westward propagating, eastward propagating, and standing waves averaged over 30–65°N and October to March. The lines and shadings are defined in the same way as in Figure 1. Note that the magnitude of the difference in wave power is at least twice as large for westward propagating waves as for eastward propagating waves.

standing waves are predominantly at wave number 2. Similarly, significant differences in wave power at wave number 2 with periods of 45-60-day are also visible for all three types of waves, except for westward propagating waves at 5 hPa or standing waves at 50 hPa. The significant differences at higher frequency shown in the total wave power spectrum (e.g. 11–13 day waves at wave number 2 and 3, see Figure 2 (right)) are mostly associated with standing waves, especially at 5 and 10 hPa, while traveling waves contribute little.

[31] Further sensitivity tests suggest that these higher frequency differences tend to wax and wane when different time periods and/or latitude bands are used. For instance, the difference in total wave power is considerably weaker in the pre-satellite era and stronger in the ERA-Interim data (see Figure 4). It is not clear to us whether or not this non-stationary behavior is an artifact of different data quality from pre- and post satellite eras, or it is a real phenomenon that is linked to decadal variability of the QBO modulation [*Lu et al.*, 2008; *Anstey et al.*, 2010]. In this study, we aim to focus on the most significant, near stationary behavior of the QBO modulation, and leave the non-stationary behavior of the relative smaller amplitude, less significant QBO signature in the 11–13 day waves for a future study. As the waves with periods of 45–60 days are exactly double the periods of the 22.5–30 day waves and the 22–23 day waves are known to be one of the dominant modes of planetary waves in the atmosphere [*Sivjee and Walterscheid*, 2002; *Pancheva et al.*, 2007, 2008a, 2008b; *Mukhtarov et al.*, 2010], the origin of those waves are likely to be similar.

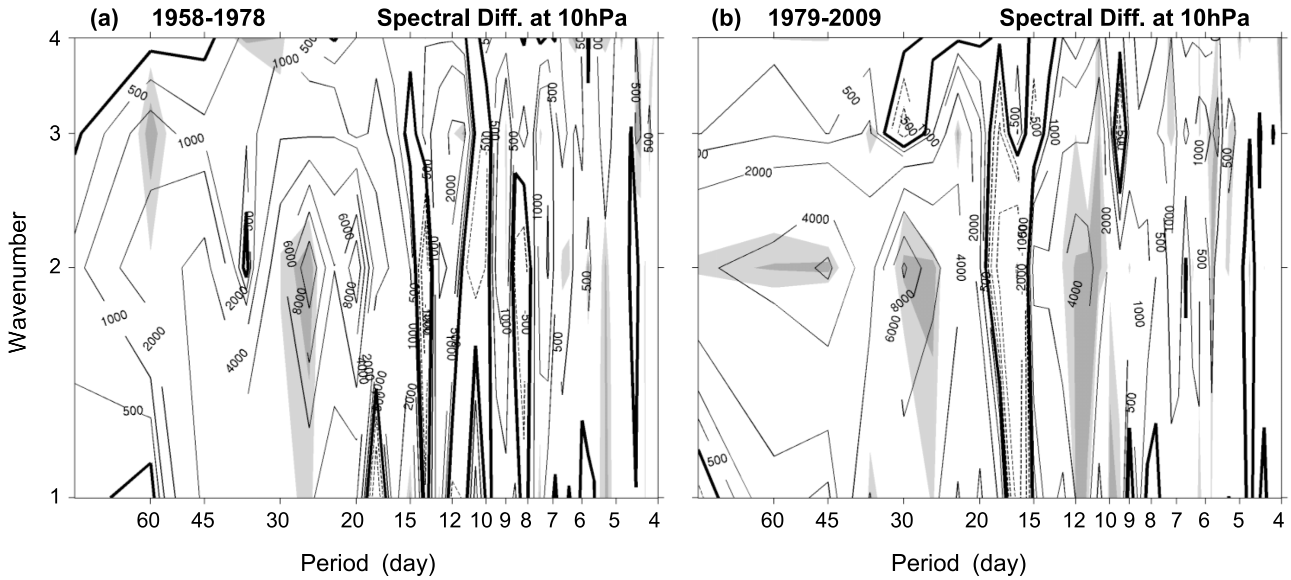

Figure 4. The spectral differences of total planetary wave power (in units of m^2) between QBOw and QBOe at 10 hPa for the sub-periods of (a) 1958–1978 and (b) 1979–2009. The lines and shadings are defined in the same way as in Figure 1.

For this reason, we shall focus on the 22.5–30 day waves only hereafter.

[32] The latitudinal distributions of the wave power for the sum of wave numbers 1 to3 with periods of 22.5–30 days at 5, 10 and 50 hPa are shown in Figure 5. It is evident that all three types of waves contribute an approximately equal amount towards the total wave power of the 22.5–30 day waves. In agreement with Figure 2, significant differences in the 22.5-30-day waves at wave numbers 1 to 3 are observed mainly at 30–65°N and they are dominated by eastward propagating and standing waves. Significant differences in westward propagating waves are found only at 10 and 5 hPa, consistent with Figure 3. The differences in westward propagating waves are found to be associated with a relatively smaller latitude band at 45–55°N where the magnitude of the differences in westward propagating waves for the two QBO phases is only half that for the eastward propagating waves. An equatorward shift of the peak difference in wave power (QBOw - QBOe) is associated with an increase in altitude for the total wave power. This shift is mainly caused by a similar shift in the eastward propagating waves.

[33] In order to study whether or not these stratospheric planetary wave differences are linked to tropospheric wave activity, the same analysis was performed for three pressure levels in the troposphere, i.e. 200, 500 and 925 hPa, for the extended (Oct-Mar), early (Oct-Dec) and late (Jan-Mar) winter. We found no significant difference in wave power for the extended or late winter periods. Significant differences were however found in early winter and for wave number 2 only. Figure 6 is similar to Figure 5 but for the wave power at 200, 500 and 925 hPa (top to bottom) for wave number 2 with periods of 22.5–30 days in early winter. Note that the wave power increases by up to 4 times from 925 hPa to 200 hPa, suggesting a rapid increase of the wave amplitudes with altitude in the troposphere. At 200 hPa, it is evident that, only under QBOw, westward propagating waves contribute more toward the total wave power than either standing or eastward propagating waves. Under QBOe, however, the contributions from all three types of waves are similar in magnitude. Significant modulation of the QBO on the waves can be observed for westward propagating waves at 55–75°N. A very similar latitudinal distribution of wave power and QBO modulation are found at 500 hPa. At 925 hPa, the QBO modulation becomes noticeably weaker; but a significant difference in wave power is still noticeable for westward propagating waves at latitudes of 45–55°N.

3.2. QBO Signature in the TIMED/SABER Temperatures

[34] In this section, we report the results from TIMED/SABER temperatures, which provide additional information on the vertical extent of the QBO effect into the mesosphere and lower thermosphere (MLT). To assess the relative contributions from each wave component and to compare their vertical structures, we have examined zonal wave number 1 to 3 individually for both eastward and westward propagating waves. The key results are presented here.

[35] Figure 7 shows the temporal evolution of 23-day eastward propagating waves at zonal wave number 1, 2, and 3 extracted from SABER temperatures at 50°N. As expected, the amplitudes of the waves tend to peak in mid-winter. In agreement with the results from the ERA-reanalyses, there is a noticeable biennial variation in the 23-day eastward propagating waves. It is particularly noticeable for zonal wave numbers 1 and 2, in which larger wave amplitudes tend to be associated regularly with QBOw while smaller wave amplitudes tend to be associated with QBOe.

[36] Figure 8 shows the magnitude and the vertical structure of the QBO modulation of the 23-day eastward propagating waves at 50°N for zonal wave numbers 1, 2 and 3. The QBO variation in the wave number 1 is mostly noticeable at altitudes of 20–70 km and appears to peak in late winter (Jan-Feb).The QBO variation in the wave number 2, however, extends only from 20 km to 45–50 km and peaks in early

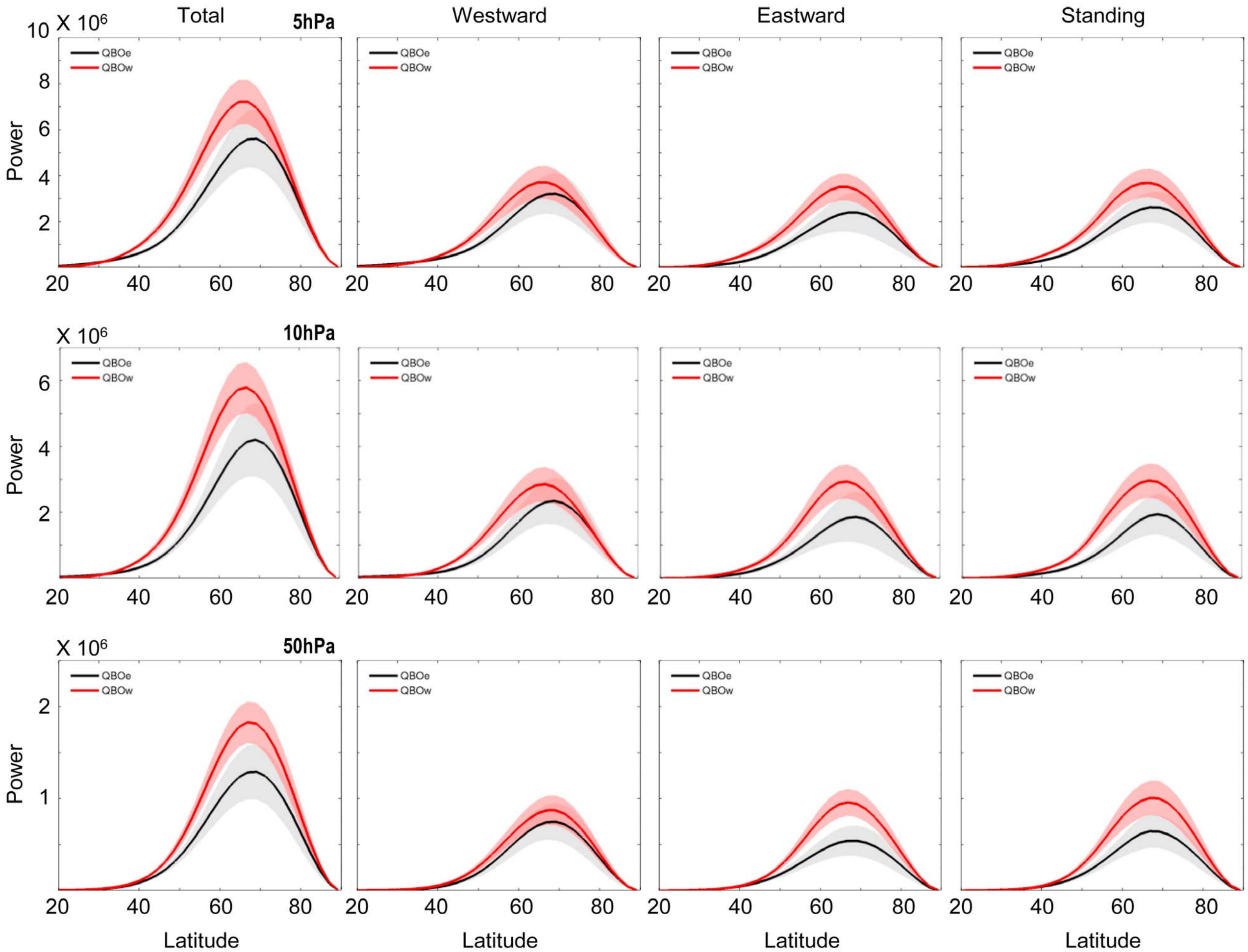

Figure 5. Wave power (in units of m^2) of (left to right) total, westward propagating, eastward propagating and standing waves at zonal wave numbers 1–3 and a period of 22.5–30 days as a function of latitude at (top to bottom) 5 hPa, 10 hPa and 50 hPa for QBOw (red line with pink shading) and QBOe (black line with gray shading) averaged from October to March. The shading indicates the 95% confidence interval.

winter (Nov-Dec) in the lower stratosphere and in mid-winter in the upper stratosphere. The QBO variation in the wave number 3 extends from 25 to 45 km and tends to peak in mid-winter (Dec-Jan). A time delay in the peak QBO variation between the lower stratosphere and the upper stratosphere and/or the mesosphere is clearly evident for all three eastward propagating waves, suggesting that the modulation originated in the lower atmosphere. In addition, the magnitude of the QBO variation reduces as the wave number increases. In general, the vertical structure of the 23-day wave amplitudes and their associated QBO modulations shows an overall weakening of wave amplitudes as well as QBO modulation at ∼45–50 km. It is unclear to us what has caused this reduction. On average, the QBO variations in the eastward propagating waves at 50°N are 0.9, 0.6 and 0.3 K, which represent about 7.7%, 6.3% and 6.3% of the mean wave amplitudes for wave number 1, 2 and 3, respectively. There is also an apparent QBO variation of the eastward propagating wave number 3 waves at 75–90 km, which appears to move downward rather than upward. Its origin remains to be discovered, but this is beyond the scope of this paper and will not be further considered hereafter.

[37] For the westward propagating waves, an apparent QBO modulation of the amplitude of wave number 1 is found only in the lower stratosphere at 20–25 km, 50°N (not shown), with larger wave amplitude associated with QBOw than with QBOe. Similar results can be obtained for zonally symmetric s = 0 oscillations (not shown). No clear QBO variation was found in wave number 2 or 3 westward propagating waves (not shown).

[38] Figure 9 summarizes the QBO modulation of the 23-day waves at 50°N. In agreement with previous results from ERA reanalyses, the amplitudes of the 23-day waves extracted from SABER temperatures are generally larger for QBOw than for QBOe. While the amplitudes of wave number 1 and 2 eastward propagating waves are comparable, a QBO modulation is most clearly associated with wave number 2 and the effect extends from 20 km to 70 km for wave number 1 and only from 20 km to 45 km for wave number 2.

[39] Regular QBO variation is also visible in wave number 3 eastward propagating waves averaged over 20–45 km, and wave number 1 westward propagating waves and zonally

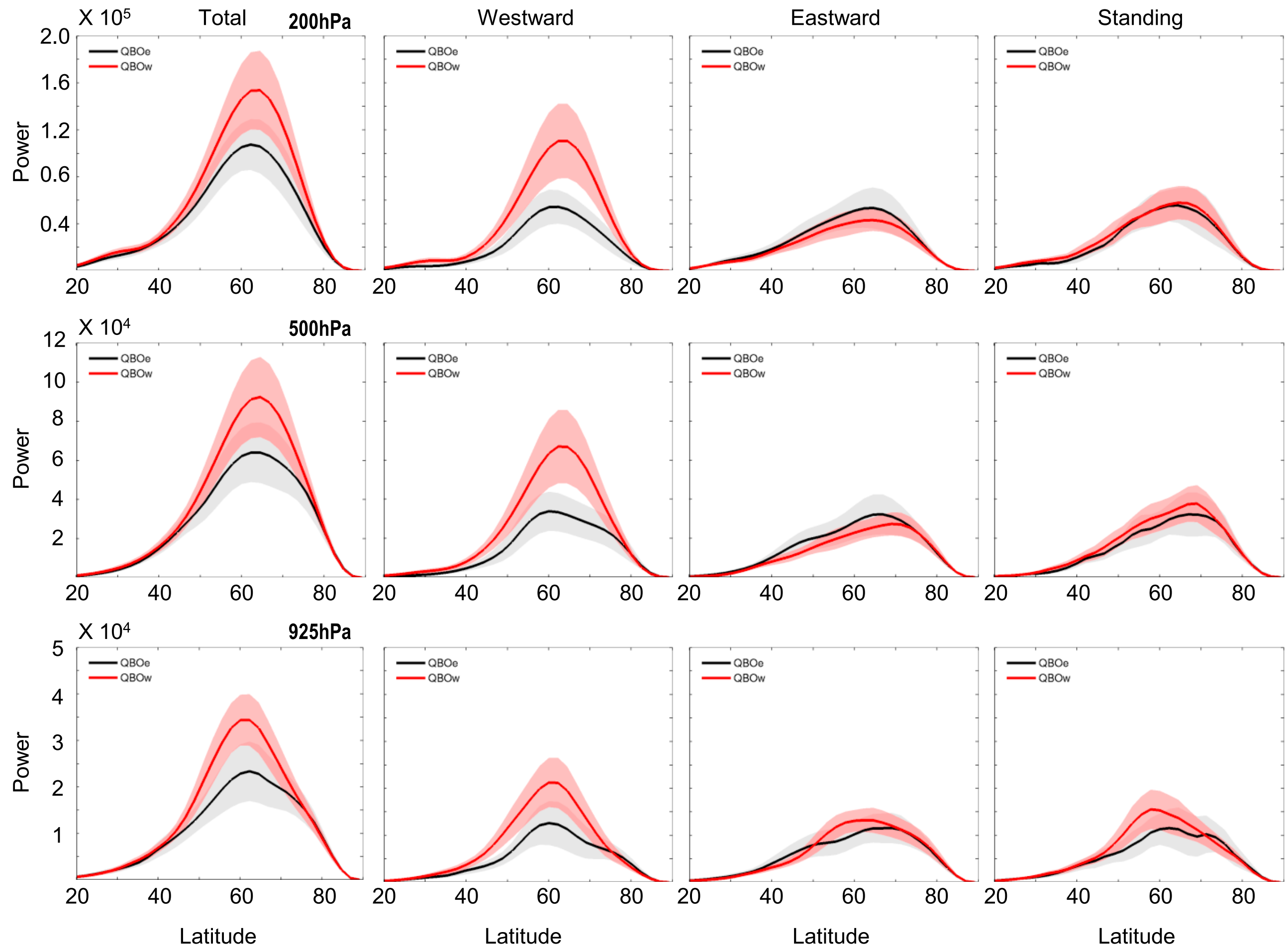

Figure 6. Wave power (in units of m^2) of (left to right) total, westward propagating, eastward propagating and standing waves at zonal wave number 2 and a period of 22.5–30 days as a function of latitude at (top to bottom) 200 hPa, 500 hPa and 925 hPa for QBOw (red line with pink shading) and QBOe (black line with gray shading) averaged from October to December.

symmetric s = 0 oscillations in the lower stratosphere (20–25 km). However, the wave amplitudes associated with those waves are only half of those in wave number 1 and 2 eastward propagating waves. Also, given the fact that the QBO effect on westward propagating waves and s = 0 oscillations is confined to 20–25 km, the results from SABER temperatures also indicate an overall stronger QBO modulation on eastward propagating than westward propagating waves in the stratosphere and mesosphere.

[40] The latitudinal structures of these same 23-day waves and zonally symmetric s = 0 oscillations are shown in Figure 10, averaged over the same vertical layers as in Figure 9. Again, in good agreement with what was detected from the geopotential height data of the ERA-reanalyses, the wave amplitudes and the QBO modulation are stronger at 50°N and become progressively weaker toward the equator, suggesting the QBO effect on those waves is largely confined to mid- to high latitudes.

4. Discussion

[41] Traveling planetary waves with a period of ~23 day are regularly observed in the NH winter stratosphere and mesosphere. For instance, ~23-day planetary waves have been observed in the NH winter stratosphere and mesosphere by analyzing the airglow brightness variability at Eureka, Canada [*Sivjee and Walterscheid*, 2002]. The low-frequency variability of the NH winter troposphere was found to be dominated by westward propagating waves with a period of ~25 days [*Branstator*, 1987; *Kushnir*, 1987]. By using the UK Met Office assimilated data and radar measurements at eight stations, *Pancheva et al.* [2008a] found that 23-day traveling waves play a significant role in the vertical coupling of the stratosphere-mesosphere after the onset of the sudden stratospheric warmings. The waves propagate vertically and can reach the upper mesosphere. 23-day traveling waves can also be generated in situ within the mesosphere by the dissipation and breaking of gravity waves filtered by stratospheric winds. *Pancheva et al.* [2007] found that besides 23-day traveling waves the NH winter stratosphere-mesosphere dynamics is also perturbed by 23-day zonally symmetric (s = 0) oscillations, which are likely generated by nonlinear coupling between the 23-day traveling and quasi-stationary planetary waves. The zonally symmetric oscillations play an important role not only in the Arctic stratosphere-mesosphere winter dynamics but also in the

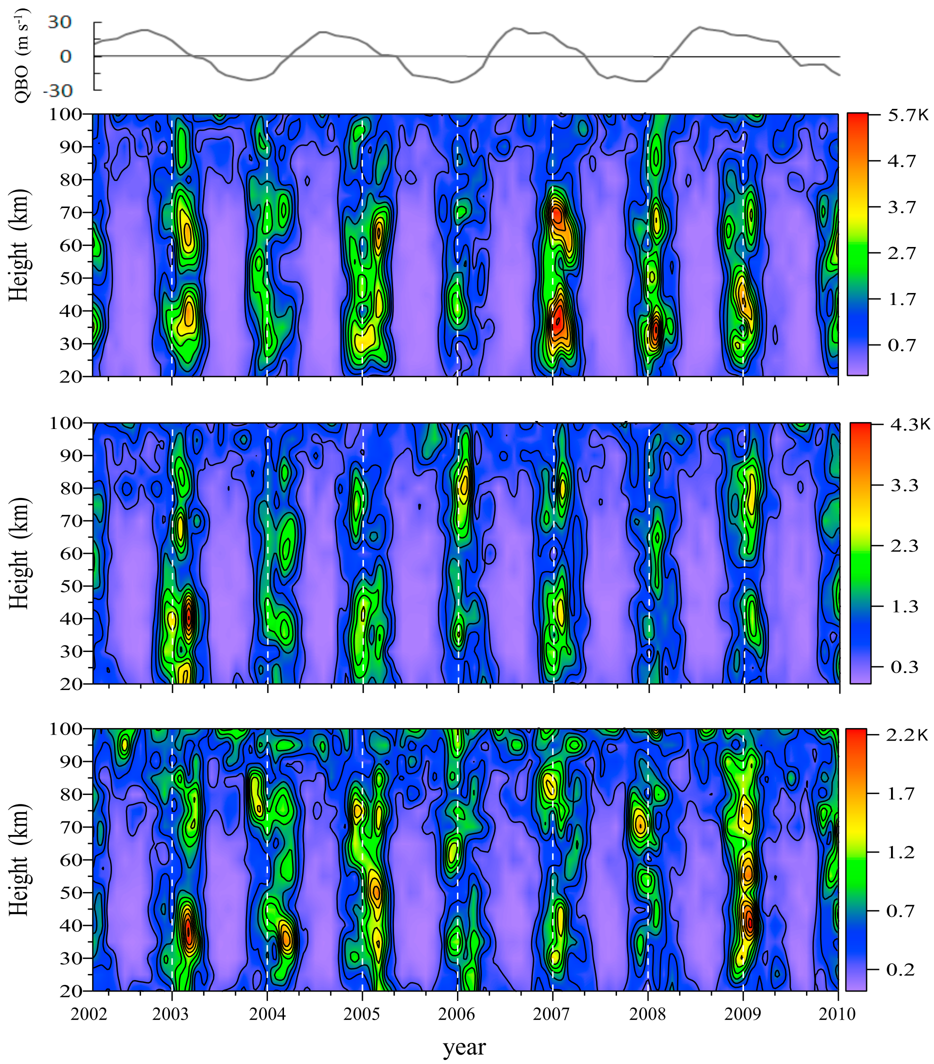

Figure 7. Time-altitude cross section of the 23-day eastward propagating wave amplitudes (in units of K) extracted from SABER temperatures for zonal wave number (top to bottom) 1, 2 and 3 at 50°N. The vertical structures are shown only up to an altitude of 100 km because the temperature variability above this level becomes much noisier and is strongly affected by solar and geomagnetic variability. The QBO (i.e., monthly zonal-mean zonal wind anomaly at 50 hPa) is shown at the very top to facilitate its phase identification.

coupling of the high and low-latitude regions [*Pancheva et al.*, 2008b]. For the first time, we have found that the 23-day waves may be modulated by the QBO and the modulation extends from the lower stratosphere to the mesosphere.

[42] Little is known about the origin of the ~23 day waves. *Fedulina et al.* [2004] have suggested that these ultra-long traveling waves are generated by internal variability of quasi-stationary planetary waves. The ~23-day waves may also be generated through nonlinear wave coupling. That is, when two primary waves with frequencies and wave numbers of (f_1, k_1) and (f_2, k_2) interact nonlinearly, they generate secondary waves which have frequencies of $f_1 + f_2$ and $|f_1 - f_2|$ and wave numbers of $k_1 + k_2$ and $|k_1 - k_2|$. A nonlinear coupling between the 16-day planetary waves and ~50-day (or 1.7-month) oscillations would generate secondary planetary waves with periods of ~23 days and 12 days.

[43] Apart from the well-known 16-day planetary waves that are known to amplify during winter, zonal mean intraseasonal oscillations (ISO) with a periodicity of ~1.7-months have indeed been observed in the atmosphere. *Mayr et al.* [2009] has found the signature of intraseasonal oscillations with periods of 1.7 and 3 months in the NCEP data for the period of 1996–2006. They have also shown that similar oscillations can be obtained by a numerical spectral model. Zonal mean ISO with periods around 1.5–2 months have been observed by *Eckermann and Vincent* [1994] in zonal and meridional winds and in the gravity wave activity inferred from medium frequency radar measurements at low latitudes in the upper mesosphere and lower thermosphere. *Huang et al.* [2005, 2006b] also reported similar zonal oscillations in the temperature measurements on the UARS and in SABER/TIMED. The QBO modulation of the 45–60 day waves might be related to the 1.7-months ISO.

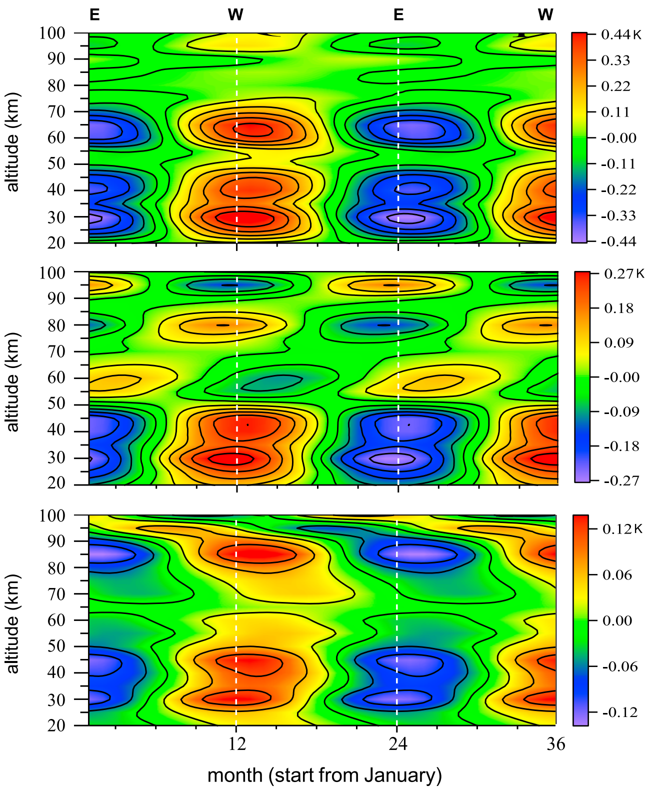

Figure 8. Time-altitude cross section of the averaged QBO amplitudes (in units of K and over 1.5 QBO cycle) of the 23-day eastward propagating waves for zonal wave number (top to bottom) 1, 2, and 3. The associated QBO phases are specified at the top; W stands for QBOw while E stands for QBOe.

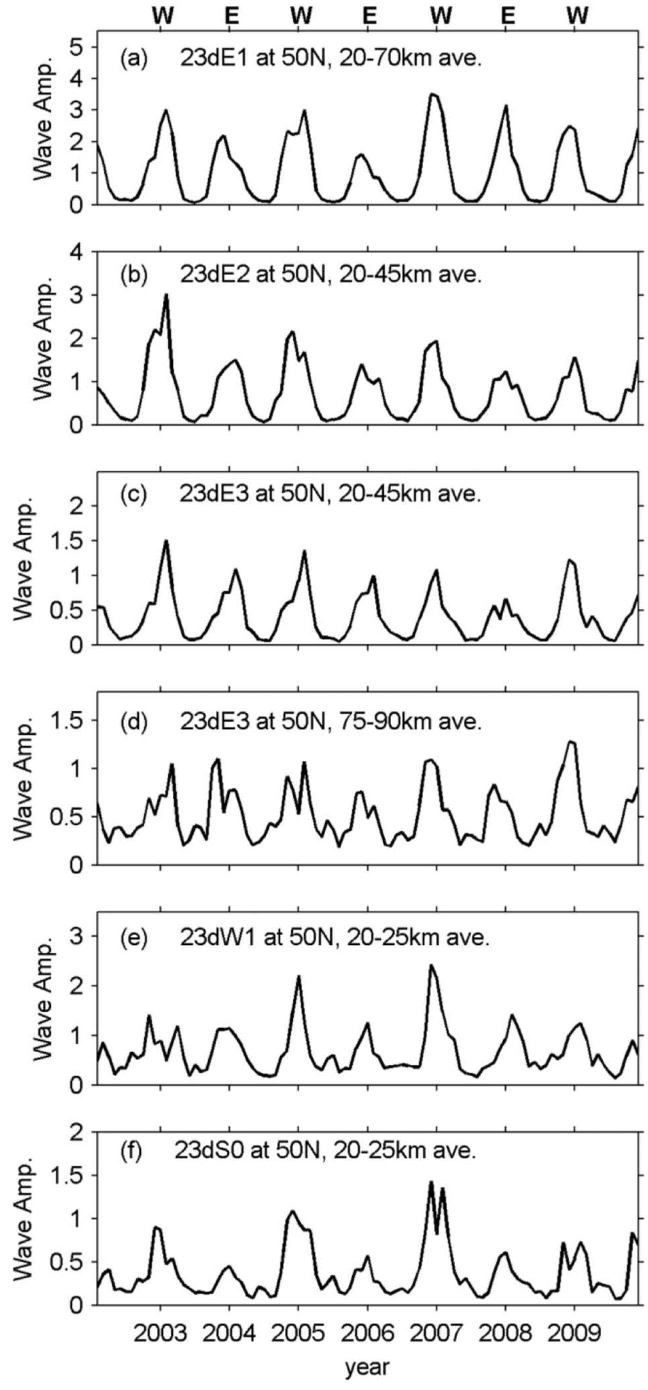

Figure 9. Amplitude (in units of K) of the 23-day traveling planetary waves at 50°N extracted from SABER temperatures for: (a) eastward propagating waves with zonal wave number 1 averaged for 20–70 km; (b) eastward propagating waves with zonal wave number 2 averaged for 20–45 km; (c) eastward propagating waves with zonal wave number 3 averaged for 20–45 km; (d) eastward propagating waves with zonal wave number 3 averaged for 75–90 km; (e) westward propagating waves with zonal wave number 1 averaged for 20–25 km; and (f) zonally symmetric s = 0 oscillations averaged for 20–25 km. The phases of the QBO for each winter period are specified at the top.

[44] One aspect of nonlinear wave coupling is that the amplitudes of the secondary waves are generally proportional to those of the primary waves. On the basis of the SABER results, we have found that the amplitudes of the 16-day and 23-day waves at wave numbers 1 to 3 are indeed proportionally distributed for both eastward and westward propagating waves. In addition, our spectral analysis has found that planetary waves with periods of 45–60, 22.5–30 and 11–13 days are all detected to be modulated by the QBO. We therefore suggest that an interaction between the QBO and the zonal mean ISO with a periodicity of ∼1.7-months is the most likely cause of the observed QBO modulation.

[45] Our results are consistent with previous studies on the QBO modulation of traveling waves [*Miyoshi and Hirooka*, 2003]. That is: traveling waves tend to be significantly stronger when the QBO in the lower stratosphere is in its westerly phases than when it is in its easterly phases. Our results are also consistent with the GCM simulations by *Naito and Yoden* [2006], who showed that the EP-fluxes in the troposphere as well as in the midlatitude lower stratosphere are stronger under QBOw than under QBOe. Equatorward (poleward) refraction of EP-flux is mainly observed equatorward of 50°N under QBOw (QBOe) in the lower stratosphere. However, we could not find any significant difference in traveling planetary activity in the high-latitude stratosphere, while *Naito and Yoden* [2006] found a reduction of EP-flux under QBOw and increase of EP-flux under

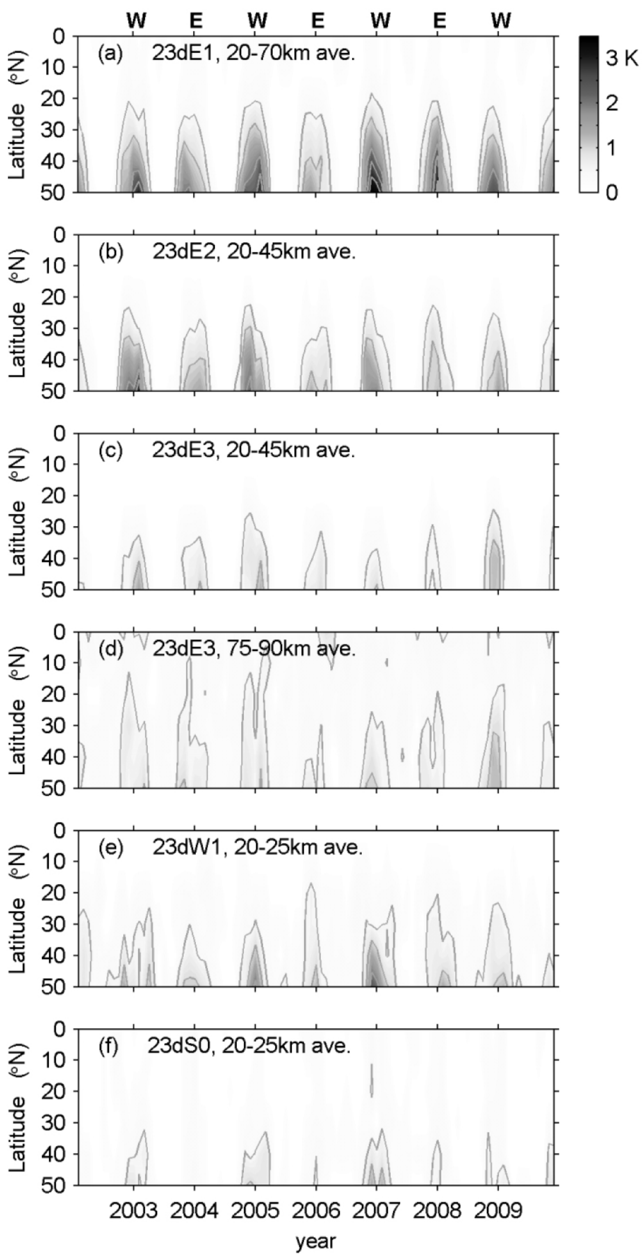

Figure 10. Time and latitude-cross section of the 23-day traveling planetary waves extracted from SABER temperatures. The wave numbers, the height ranges over which the amplitudes of the waves are averaged and the phases of the QBO are the same as in Figure 9.

QBOe there. The difference in EP-flux at high latitude obtained by *Naito and Yoden* [2006] may be mostly due to a QBO modulation of quasi-stationary rather than traveling planetary waves. Also using SABER temperature data, weaker quasi-stationary planetary waves at wave number 1 were found to be associated with QBOw than with QBOe at 50°N [*Mukhtarov et al.*, 2010]. It is not clear why the QBO modulation on the planetary waves in the stratosphere and above is opposite for quasi-stationary and traveling planetary waves. Nevertheless, this opposite behavior suggests that, in order to avoid cancellation of the signals, it is necessary to assess the effect of the QBO on the quasi-stationary and traveling planetary waves separately. We speculate that the waxing and waning responses in stationary wave numbers 1 and 2 in early and late winter reported previously may be partly due to a contamination effect of the traveling planetary waves. In particular, the effect of ultra-long traveling waves may not be properly eliminated if 30- to 60-day time segments are used.

[46] It has been reported that, in the troposphere, the interaction between quasi-stationary and traveling planetary waves tends to provide energy to westward propagating waves and extract energy from the eastward mode [*Kao and Lee*, 1977]. Considering this, stronger westward propagating waves associated with QBOw might be linked to anomalously enhanced interaction between quasi-stationary and traveling planetary waves in the troposphere. Further studies are required to understand how the QBO may affect this interaction.

[47] It is also worth noting that significant QBO modulation of the westward propagating waves is observed at high latitudes in the troposphere while a stronger QBO effect on the eastward propagating waves is obtained in the stratosphere. It implies anomalously stronger dissipation (excitation) of westward (eastward) propagating waves in the lower stratosphere under QBOw than under QBOe. It has been suggested that changes in the quasi-stationary planetary waves cause excitation of ultra-long traveling planetary waves, provided that the background wind has temporal changes, preferentially in the tropics [*Smith*, 1985; *da Silva and Lindzen*, 1987]. *Hayashi and Golder* [1983] pointed out that nonlinear wave-wave interactions represent a very important excitation mechanism for the westward propagating waves in the troposphere. Nevertheless, it remains intriguing that the QBO modulation on wave number 2, 22.5–30 day waves occurs in the troposphere during early winter, while the QBO signals are significant for the whole winter period (Oct-Mar) in the stratosphere. Further modeling studies are required to fully understand how midlatitude tropospheric westward propagating waves with periods of 22.5–30 days can be enhanced under QBOw.

[48] The QBO modulation on the 22.5–30 day and 45–60 day waves reported here is valid for the extended period (i.e. 1958–2009) in which decadal-scale variation is largely averaged out. Our sensitivity tests suggest that higher frequency variations are more sensitive to the time period under consideration while variations at lower frequency are less sensitive to this. This implies a more non-stationary behavior of higher frequency waves (with periodicity < 22.5 days), which might be linked to decadal-scale variation in the QBO-vortex coupling. More studies are needed to understand how the 11-year solar cycle [*Labitzke and van Loon*, 1988; *Naito and Hirota*, 1997; *Lu et al.*, 2009], the seasonal alignment of QBO phase transitions with the annual cycle [*Hampson and Haynes*, 2006] and/or stratospheric bimodality [*Christiansen*, 2010] are linked to higher frequency planetary waves (with periodicity < 22.5 days) at decadal scales.

5. Conclusions

[49] It has been proposed that a change of the critical line position caused by the QBO in the equatorial lower stratosphere induces a change in the waveguide of the

quasi-stationary planetary waves [*Holton and Tan*, 1980, 1982]. Based on a space-time spectral analysis of ERA-reanalysis geopotential data for the period of 1958–2009, here we have shown that the QBO also modulates traveling planetary waves in the midlatitude stratosphere and in the high-latitude troposphere. The results from ERA reanalyses data were further confirmed by the wave amplitudes extracted from SABER/TIMED temperature data from 2002 to 2009.

[50] In essence, the QBO modulation on the planetary waves during NH winter is marked by significant changes in the wave spectrum at two periodicity regimes: 22.5–30 days and 45–60 days. In terms of vertical and latitudinal structure, the QBO modulation of the 45–60 day waves is similar to that of the 22.5–30 day waves. Planetary waves with periods of 11–13 days also appear to be modulated by the QBO but the effect is largely confined to pre-satellite period. Further study is needed to understand the non-stationary behavior of the QBO modulation of the 11–13 day waves so that we know whether or not it is due to a difference in data quality between pre- and post- satellite eras or links to the decadal-scale variation of the Holton-Tan effect [*Lu et al.*, 2008; *Anstey et al.*, 2010].

[51] Focusing on the 22.5–30 waves, we have found the following:

[52] 1. In the stratosphere, there is an overall increase of 22.5–30 day traveling waves under QBOw and an overall reduction of those waves under QBOe. This behavior is applicable for the whole winter (Oct-Mar), showing little difference between early and later winter. For both the mean state and the wave components, the strongest signature is found at 10 hPa.

[53] 2. The strongest and most consistent QBO modulation is associated with zonal wave number 2 both in the stratosphere and troposphere. It appears that this QBO modulation originates from the troposphere as the tropospheric signals are found in early winter, while stratospheric signals emerge from middle to late winter. Wave numbers 1 and 3 also contribute to changes in the stratosphere, but the origins of the QBO modulation on these waves most likely lie in the lower stratosphere.

[54] 3. The QBO modulation is stronger for westward propagating waves in the troposphere at ∼55–75°N and stronger for eastward and standing waves in the stratosphere at ∼35–65°N. The QBO effect on eastward propagating waves starts near the tropopause or in the lower stratosphere. The QBO modulation shifts equatorward with altitude and the effect is most significant for eastward propagating waves. The change in wave propagation occurs throughout the depth of the stratosphere and the equatorward shift of the modulation increases with altitude; this becomes particularly noticeable at 5–10 hPa.

[55] 4. Consistent results in the stratosphere are obtained from SABER temperatures. The strongest QBO modulation is associated with 23-day eastward propagating waves. The SABER data further show that the QBO modulation on these waves extends upwards to 70 km for wave number 1 and to 45 km for wave number 2. The modulation on wave number 3 waves also goes up to 45 km but the magnitude is only half of that associated with wave numbers 1 and 2. In addition, there is an apparent QBO modulation of eastward propagating 23-day waves at wave number 3 at 75–90 km altitude.

[56] We suggest that the ∼23-day waves are generated by a nonlinear interaction between zonal-mean intraseasonal oscillations (ISO) [*Mayr et al.*, 2009] and the well-known 16-day planetary waves. A QBO-ISO interaction is the source of the detected QBO modulation on the ∼23-day waves. Further studies are needed to prove this hypothesis and, in particular, to understand the mechanism through which the QBO modulate the dissipation/excitation of the traveling planetary waves.

[57] **Acknowledgments.** H.L. is funded by the Natural Environment Research Council (NERC), UK. I.C. is partially funded by NERC as well as by the National Center for Atmospheric Research, which is sponsored by the National Science Foundation. We are grateful to ECMWF for providing the geopotential height data from their reanalysis products and the SABER team for access to the data on http://saber.gats-inc.com. We thank Tony Philips at British Antarctic Survey for help with acquiring and managing the ERA-40 and ERA-Interim data. Finally, we thank three anonymous reviewers for their constructive comments.

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