EARLY ONLINE RELEASE

This is a PDF of a manuscript that has been peer-reviewed and accepted for publication. As the article has not yet been formatted, copy edited or proofread, the final published version may be different from the early online release.

This pre-publication manuscript may be downloaded, distributed and used under the provisions of the Creative Commons Attribution 4.0 International (CC BY 4.0) license. It may be cited using the DOI below.

The DOI for this manuscript is
DOI:10.2151/jmsj.2018-057

J-STAGE Advance published date: October 5th, 2018

The final manuscript after publication will replace the preliminary version at the above DOI once it is available.
Response of the Southern Hemisphere Atmosphere to the
Stratospheric Equatorial Quasi-Biennial Oscillation (QBO)
from Winter to Early Summer

Yousuke YAMASHITA¹
Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa, Japan;
National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan

Hiroaki NAOE
Meteorological Research Institute, Tsukuba, Ibaraki, Japan

Makoto INOUE
Department of Biological Environment, Akita Prefectural University, Akita, Japan

Masaaki TAKAHASHI
National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan

¹) Corresponding author: Y. Yamashita, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 236-0001, JAPAN.

Email: yyousuke@jamstec.go.jp
Abstract

We investigate the effects of the stratospheric equatorial quasi-biennial oscillation (QBO) on the extratropical circulation in the Southern Hemisphere (SH) from SH winter to early summer. The Japanese 55-year Reanalysis (JRA-55) dataset is used for 1960–2010. The factors important for the variation of zonal wind of the SH polar vortex are identified via multiple linear regression, using Equivalent effective stratospheric chlorine (EESC), middle- and lower-stratospheric QBO, solar cycle, El Niño-Southern Oscillation (ENSO), and volcanic aerosol terms as explanatory variables. The results show that the contributions to the SH polar vortex variability of ENSO are important in SH early winter (June) to mid-winter (July), while that of middle-stratospheric QBO is important from spring (September to November) to early summer (December).

Analyses of the regression coefficients associated with both middle- and lower-stratospheric QBO suggest an influence on the SH polar vortex from SH winter through early summer in the seasonal evolution. One possible pathway is that the middle-stratospheric QBO results in the SH low-latitudes stratospheric response through the QBO-induced mean meridional circulation, leading to a high-latitude response. This favours delayed downward evolution of the polar-night jet (PNJ) at high latitudes (around 60°S) from late winter (August) to spring (September–November) during the westerly phase of the QBO, consequently tending to strengthen westerly winds from stratosphere to troposphere in SH spring. The other possible pathway involves the response to lower-stratospheric QBO that induces the SH late winter increase in upward
propagation of planetary waves from the extratropical troposphere to stratosphere, which is consistent with weakening of the PNJ.

1. Introduction

Globally homogeneous spatial and temporal data coverage of the stratosphere has been provided by satellite observations since the latter half of the 1970s, and year-to-year variability and seasonal variation have been investigated, due to the accumulation of observational data, in both the Northern (NH) and Southern (SH) Hemispheres. The year-to-year variability of the stratospheric polar jet over the NH is very large during NH winter and spring, and 6 times a decade includes a complete reversal of the upper stratospheric westerlies in association with sudden stratospheric warming (SSW) (e.g., Labitzke 1977, 1982; Naujokat 1981; Shiotani et al. 1993). In the SH, such dramatic change of the stratospheric jet does not occur due to the smaller planetary wave activities than NH (exceptions include minor warming in 1988 and major warming in 2002; see Hio and Yoden 2005), and the upper-stratospheric westerly jet shifts gradually poleward and downward (hereafter “shift-down,” as in previous studies) from SH late winter to spring at the timing of final warming (the westerly jet in the winter hemisphere is replaced by the easterly jet in the summer hemisphere) (e.g., Harwood 1975; Hartmann 1976; Hirota et al. 1983; Shiotani and Hirota 1985). By using a 10-year short-term dataset from the Stratospheric Sounding Unit onboard the TIROS-N NOAA satellite, Shiotani et al. (1993) first found that the seasonal march of the stratospheric westerlies over the SH varies from year to
year with planetary wave activity. They showed that the year-to-year variability of the intensity and position of the stratospheric polar jet in the SH midwinter influences the shift-down of the polar jet in the SH late winter and spring associated with the year-to-year variability of upward propagation of planetary waves from the troposphere into the stratosphere.

Several studies have examined possible linkages between the year-to-year variability of the SH polar vortex and long-term variations, such as the equatorial quasi-biennial oscillation (QBO) in tropical stratospheric zonal winds (e.g., Holton and Tan 1980; Baldwin and Dunkerton 1998), 11-year solar cycle (e.g., Kuroda and Kodera 2005), El Niño-Southern Oscillation (ENSO) (e.g., Hitchman and Rogal 2010), and the Antarctic ozone depletion that occurred during the last four decades of the 20th century (e.g., Thompson and Solomon 2002; Son et al. 2008; Akiyoshi et al. 2009; Eyring et al. 2010; McLandress et al. 2011; Thompson et al. 2011; World Meteorological Organization 2011; Grise et al. 2013).

Holton and Tan (1980) reported that the NH polar vortex is stronger during the westerly (hereafter QBO-W) phase of the 50 hPa equatorial QBO in NH winter (termed the Holton–Tan relationship). They also showed that the response of the SH polar vortex to the QBO in September–November (SH spring) indicated a stronger westerly of the SH polar vortex during the QBO-W as the NH polar vortex, although the signals are weak. In addition to the zonal wind response, for the SH spring, Garcia and Solomon (1987) suggested that the biennial variation of the October minimum ozone in the polar region from 1979 to 1986 might have been due to the influence of the equatorial QBO defined at 50 hPa. Subsequent works noted that the
response of the SH polar vortex to the equatorial QBO (i.e., a stronger westerly during the QBO-W) was best seen in November using the equatorial QBO defined at 20–30 hPa (Baldwin and Dunkerton 1998; Naito 2002; Anstey and Shepherd 2014), and the SH QBO response was significantly observed in September–November using the equatorial QBO defined at 10–20 hPa (Hitchman and Huesmann 2009). Thus, several studies have discussed that the stratospheric QBO is closely associated with the SH polar vortex. However, the mechanism by which the QBO modulates extratropical circulation over the SH is poorly understood, as the various studies employed different height levels and metrics to define the phase of the QBO.

On the other hand, there are some indications of a linkage between the QBO and wave activities over the SH (e.g., Newman and Randel 1988; Naito 2002). Newman and Randel (1988) indicated that the biennial variation of polar vortex was consistent with variation of planetary wave forcing over the SH. Naito (2002) further analyzed the QBO influences on the Eliassen and Palm (E–P) flux in the SH and showed that the QBO at the 20–30 hPa level leads to the E–P flux signal for planetary scale waves with zonal wavenumbers 1–3 in the stratosphere. However, they employed composite analysis to determinate the atmospheric fundamental characteristics based on the meteorological data, which possibly include other signals such as solar cycle and ENSO other than response to the stratospheric QBO. Therefore, we examine the dynamical process in the SH, using multiple linear regression to separate the influences of the QBO and other factors on the SH polar vortex. In addition, the middle- and lower-stratospheric QBO are defined by two orthogonal QBO components obtained from empirical
orthogonal function (EOF) analysis, and the contributions of both the middle- and lower-stratospheric QBO to the atmospheric field over the SH are evaluated. We focus on the seasonal evolutions of SH polar vortex variability associated with the QBO and the other factors, and elucidate features of the beginning and development of the QBO-SH polar vortex relationship. During the SH winter to spring, the interaction between stratosphere and troposphere can occur through planetary waves under propagation conditions of westerly wind region in the SH stratosphere (see Section 3.1).

The paper is organized as follows. The reanalysis data and the analysis method are described in Section 2. The results are presented in Section 3. A summary is provided in Section 4.

2. Data and analysis method

2.1 Data

The primary data used in this study are the Japanese 55-year Reanalysis (JRA-55) dataset (Kobayashi et al. 2015). The JRA-55 reanalysis system is based on the TL319 horizontal resolution version of the Japan Meteorological Agency (JMA) operational data assimilation system from 1000 to 0.1 hPa with 60 vertical levels. We used the 6-hourly samples of reanalysis products from 1960 to 2010 with 1.25° × 1.25° longitude–latitude grids of 37 vertical levels, from 1000 to 1 hPa, for wind and temperature data.
2.2 **Analysis of wave propagation and circulation**

To clarify the dynamical processes of the extratropical circulation over the SH associated with the stratospheric QBO, we used the E–P flux and the residual mean meridional circulation derived from the primitive equation on the sphere (e.g., Andrews et al. 1987) with the daily mean of the JRA-55 zonal wind, meridional wind, vertical wind, and temperature data. The divergence of the E–P flux is connected with the eastward acceleration by wave activities. These variables have been used in many studies, to investigate connections between the QBO and extratropical circulation (e.g., Holton and Tan 1982; Niwano and Takahashi 1998; Chen and Li 2007; Yamashita et al. 2011; Inoue et al. 2011; Garfinkel et al. 2012; Lu et al. 2013).

2.3 **Multiple linear regression analysis**

Multiple linear regression analysis was used to examine which factors are important for the variability of atmospheric fields over the SH. This was applied to the 51-year (1960–2010) monthly-mean meteorological variables, such as zonal mean wind and E–P flux, to analyze seasonal evolution in the stratosphere and troposphere, focusing on year-to-year variability of the SH polar vortex.

Based on Crooks and Gray (2005), Austin et al. (2008), Akiyoshi et al. (2009), Yamashita et al. (2010), and Mitchell et al. (2015), we perform multiple regression analysis, including the constant, Equivalent effective stratospheric chlorine (EESC), solar cycle phase, two QBO phases, ENSO, and volcanic aerosol terms.
The following regression equation was used:

\[
Y(t) = c_0 + a_{EESC}(t) + \beta_a QBOa(t) + \beta_b QBOb(t) + \gamma_{Solar}(t) + \delta_{ENSO}(t) + \varepsilon_{Vol}(t) + R(t),
\]

where \( Y(t) \) is the target variable for regression at time \( t \) [month]. The long-term annual-mean constant and seasonally varying intercept are included in the regression coefficient \( c_0 \) as

\[
c_0 = A_0 + \sum_{j=1}^J [A_j \cos(2\pi j t/12) + B_j \sin(2\pi j t/12)],
\]

where \( J = 4 \) and \( A_j \) and \( B_j \) are Fourier coefficients.

The time series of the explanatory variables for the regression analysis that we used here are EESC term (EESC), two QBO components (QBOa and QBOb, which are defined below), solar cycle (Solar), El Niño-Southern Oscillation (ENSO), and volcanic aerosol (Vol). The seasonally varying coefficients describing the influence of the explanatory variables are denoted as \( \alpha, \beta_a, \beta_b, \gamma, \delta, \) and \( \varepsilon. R(t) \) indicates the residual variation that is not described by the regression model. An error estimation for the regression coefficient was described by Randel and Cobb (1994). The 1\( \sigma \) and 2\( \sigma \) statistical significances are indicated where the statistical fits are significantly different from zero at the 1\( \sigma \) and 2\( \sigma \) levels. We mainly discuss the regression coefficients for two QBO phases, and their results are mainly presented in Sections 3.3 and 3.4.

Defining two orthogonal QBO phase, we use the first two principal components (PCs) of monthly mean zonal wind data for the 10–70 hPa levels of the equatorial stratosphere using an empirical orthogonal function (EOF) analysis, as performed by Crooks and Gray (2005), Taguchi (2010), and Mitchell et al. (2015). We then discuss the response of the atmosphere in the SH to the QBO as defined by the regression terms corresponding to the two QBO indices.

The indices of \( QBOa(t) \) and \( QBOb(t) \) are the first two PCs derived from the monthly mean
equatorial zonal wind data at the 10, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, and 70 hPa levels. The zonal wind data are based on rawinsonde observations at Canton Island (2.46°S, 171.43°W), Gan, Maldives (0.41°S, 73.09°E), and Singapore (1.22°N, 103.55°E) provided by the International Global Atmospheric Chemistry (IGAC) / the Stratosphere–Troposphere Processes and their Role in Climate (SPARC) Chemistry–Climate Model Initiative (CCMI) (Morgenstern et al. 2017). To derive the PCs, the time series of zonal wind data was deseasonalized and then smoothed with a 5-month running mean to remove month-to-month variation (for details see Wallace et al. 1993, Taguchi 2010); then, the covariance matrix of zonal wind was solved to determine the EOFs and corresponding PCs. The sum of variances of the first (55%) and second (41%) modes account for 96% of the total variance. We confirmed that the temporal behaviors of the first and second modes of the zonal wind can best describe the evolutions of the equatorial zonal wind at 10–20 hPa and 30–50 hPa, respectively. Thus the regression coefficient of \( QBOa(t) \) indicates the variations synchronized with the middle-stratospheric QBO, while that of \( QBOb(t) \) describes the variations synchronized with the lower-stratospheric QBO.

Since this study focuses on the SH polar vortex in SH spring, the EESC term is included to account for possible effects of ozone depletion over this period (e.g., Newman et al. 2007). The index of \( EESC(t) \) was derived from the EESC index displayed in Figure 3(d) of Newman et al. (2007) (hereafter N07EESC) as

\[
EESC(t) = \frac{[N07EESC(t) - AVR(N07EESC)]}{SD(N07EESC)},
\]
where $AVR(N07EESC)$ is the mean value of the N07EESC and $SD(N07EESC)$ is its standard deviation.

Since the atmospheric field over the SH is affected by various factors including the solar cycle and ENSO, terms other than the QBO are included in the regression equation. The index of the solar cycle $Solar(t)$ was derived from Ottawa/Penticton 10.7 cm solar radio flux ($F10.7$) data provided by the NOAA/National Geophysical Data Center (NGDC) as

$$Solar(t) = [F10.7(t) - AVR(F10.7)] / SD(F10.7),$$

where $AVR(F10.7)$ is the mean value of the F10.7 index and $SD(F10.7)$ is its standard deviation. The time series of F10.7 data were smoothed in advance with a 5-month running mean. The index for the ENSO was derived from the 5-month running mean data of the Nino 3.4 index (NINO3.4) provided by the NOAA/Earth System Research Laboratory (ESRL) (http://www.esrl.noaa.gov/psd/data/correlation/nina34.data) and was calculated with $ENSO(t) = [NINO3.4(t) - AVR(NINO3.4)] / SD(NINO3.4)$. The index of volcanic activity was derived from the 5-month running mean for optical thickness ($\tau$) at 550 nm integrated from the 15 to 35 km levels, provided by the IGAC/SPARC CCMI as $Vol(t) = [\tau(t) - AVR(\tau)] / SD(\tau)$.

3. Results

3.1 Seasonal behaviors of the SH polar-night jet and its interannual variation

Figure 1a shows the seasonal change of climatological zonal-mean zonal wind at 60°S and 10 hPa. The shading represents one standard deviation of annual zonal wind during the whole
period. The zonal wind reaches its maximum in August, and the interannual variability has large magnitude from August to November. The results are in agreement with those of Hio and Yoden (2005). We here focus on temporal behaviors of the location of the polar-night jet (PNJ) in the climatological field. Figure 1b shows the latitude–height section of the seasonal evolution of the PNJ axis position (circles) from 1 August to 31 December (the first day of each month is shown as a cross), where the PNJ axis is defined as the zonal wind maximum in the latitude–height plane over 20–90°S, 1–100 hPa. Note that almost all levels of the PNJ axis in April–July are located at 1 hPa and higher (in this case, the PNJ axis position is determined at 1 hPa), where the vertical resolution of the JRA-55 data is coarse; thus, the PNJ axis position in April–July is not shown. In August (late winter), the PNJ axis is located at around 60°S, 2 hPa, leading to southward and downward movement of the PNJ axis until spring (October–November) (e.g., Kodera and Kuroda 2002), together with gradually decreasing zonal wind intensity. The timing of the shift-down is consistent with the decrease in zonal-mean zonal wind at 10 hPa from September to December (Fig. 1a). Therefore, we use the zonal-mean zonal wind at 60°S, 10 hPa as the indicator of seasonal behavior of the PNJ.

3.2 Seasonal evolution of the multiple regression terms

We estimated respective terms of the multiple linear regression equation for the zonal-mean zonal wind. Table 1 shows the monthly regression coefficients for EESC (EESC; $\alpha$), two QBO components (QBOa and QBOb; $\beta_a$ and $\beta_b$), solar cycle (Solar; $\gamma$), El Niño-Southern...
Oscillation (ENSO; $\delta$), and volcanic aerosol (Vol; $\varepsilon$) averaged over 40–80°S, 1–200 hPa. From spring to early summer, $\beta_a$, variations synchronized with the middle stratospheric QBO, are dominant, with a maximum in November. For instance, $\beta_a$ in September is $0.42 \pm 0.22$, which is more than double the other coefficients, $\beta_b$, $\gamma$, and $\delta$. Coefficients $\varepsilon$ and $\beta_b$ are more dominant than $\beta_a$ in late winter (August) and winter (June–August), respectively. Coefficient $\alpha$ is more dominant during November–December, $\delta$ is more dominant during June–July, and $\varepsilon$ is more dominant in August. These results indicate that the impacts of the EESC, ENSO, and volcanic activities on the atmospheric fields in the SH (i.e., $\alpha$, $\delta$, and $\varepsilon$) are not negligible during the analysis period. However, we here focus on the spatial distributions of $\beta_a$ and $\beta_b$ to clarify the dynamical contributions of the middle- and lower-stratospheric QBO to the SH circulation, because the contribution of QBO to the SH polar vortex is dominant from spring (September to November) to early summer (December).

Figure 2 shows the latitude–time sections of the multiple regression coefficients (black contours) of two QBO components (QBOa and QBOb), together with the $1\sigma$ and $2\sigma$ statistical significance levels (light and dark shading) where the $1\sigma$ and $2\sigma$ statistical errors exceed the absolute values of the regression coefficients. Hereafter, the regression coefficients $\beta_a$ and $\beta_b$ describing the influence of the explanatory variables of QBOa and QBOb are called “QBOa signal” and “QBOb signal,” respectively. It should be noted that similar signals are derived from different time intervals in the JRA-55 dataset of 1958–2017, 1960–1978, 1979–2010, and 1979–2017, and signals similar to the JRA-55 are derived from JRA-55C (an atmospheric
reanalysis assimilating conventional observations only) and ERA-interim for the same time interval of 1979–2010 (not shown). Note that the similar signals are derived from the regression with La Niña and El Niño years separately, with slightly early change over mid- and high-latitudes in El Niño years (not shown). The green contours in Fig. 2 indicate zonal-mean zonal wind at 10 hPa in the climatological component (coefficient $c_0$). Except for late spring and summer (November–February), westerlies are dominant in the mid- and high-latitudes at 10 hPa. The position of the maximum westerly wind, which is representative of the PNJ axis, moves from 70°S to 60°S during April–August, with largest magnitude (>80 m s$^{-1}$) occurring in August. The maximum of the westerly wind moves to the polar region with gradual decrease until November, in agreement with the decrease in wind speed at 10 hPa, as shown in Fig. 1a.

We first discuss the QBOa westerly signal of zonal wind. The temporal variation of the QBOa coefficient shows that the westerly signal at 0–30°S in midwinter (July) appears to extend poleward toward the Antarctic in late winter and spring (August–November). The westerly wind signal has a maximum of 3 m s$^{-1}$ around 65°S in November at a statistical significance level of 2$\sigma$ (Fig. 2a). Figure 3a shows the latitude–height section of the QBOa coefficient in November, when a strong westerly wind is shown in mid- and high-latitudes in Fig. 2a. The westerly maximum at 10–20 hPa around the equator corresponds to positive values of $\beta_a$ near 10–20 hPa. This means that the QBOa signal found in mid- and high latitudes can be regarded as the influence of the equatorial middle-stratospheric QBO. $\beta_a$ is positive (i.e., westerly wind signal) throughout the extratropical stratosphere. In addition, the maximum westerly signal is located
near the zero-wind line of the climatological zonal wind (65°S and 5–10 hPa). These findings imply that the westerly wind area in the extratropical stratosphere is extended to more upper levels in the QBO-W condition, and the PNJ over the SH remains strong for a longer time. In other words, the westerly phase of middle-stratospheric QBO favours a delay in the PNJ shift-down. The westerly signal extending from the SH mid-latitudes to the Antarctic at the late timing of the shift-down is similar to the results of Anstey and Shepherd (2014), who showed the seasonality in the response of the SH westerly wind to the QBO-W defined 20 hPa.

Figures 2b and 3b show regression coefficients of the QBOb ($\beta_b$; black contour) for zonal-mean zonal wind in the time–latitude and latitude–height sections, respectively. We find the QBOb signal of zonal wind at the equator, with a westerly maximum at 30–50 hPa (Fig. 3b). This means that the QBOb signal found in mid- and high latitudes is regarded as the response to the equatorial lower-stratospheric QBO. Similarly to the QBOa signal, the positive values of $\beta_b$ (i.e., the westerly wind signal) are found in the mid- and high-latitude stratosphere in SH spring (October–November), with statistical significance (Fig. 2b), suggesting that the shift-down of the PNJ is delayed in the QBO-W condition at 30–50 hPa. In contrast to the QBOa effects, the westerly signal that is found around 30–40°S in June–July disappears in August, and further southward movement of the westerly signal is not detected in late winter and spring (Fig. 2b).

3.3 Middle-stratospheric QBO westerly effects on the seasonal evolution of the
To investigate how the response of SH polar vortex to the middle-stratospheric QBO arises in winter and spring, the seasonal evolutions of the zonal wind, temperature, residual mean meridional circulation, and wave propagation using E–P flux were analyzed. Figures 4a–4d show latitude–height sections for the QBOa signals of zonal wind from July to October; Figures 4e–4h show those of temperature (contour) with residual mean meridional circulation (vector); and Figures 4i–4l show those of the zonal wavenumber 1–3 (WN1–3) components of E–P flux (vector) with its divergence (contour).

In July, there is an easterly signal ($\beta_a < 0$) at around 1 hPa that lies over a westerly signal ($\beta_a > 0$) at around 10–20 hPa in the equatorial region (10°N–30°S) (Fig. 4a). Residual circulation analysis revealed a two-cell structure of the meridional circulation signal in the equatorial region with a southward flow signal at 2 hPa, an equatorward flow signal at 10–20 hPa, and a southward signal at 50–100 hPa (Fig. 4e). The upper cell corresponds to the upward flow signal around the equator, and the downward flow signal at 20–50°S around 2–10 hPa levels (Fig. 4a) corresponds to the QBO’s easterly wind shear in vertical; the lower cell corresponds to the downward flow signal around the equator, and the upward flow signal at 20–50°S around 20–50 hPa levels (Fig. 4a) corresponds to the QBO’s westerly wind shear in vertical, suggesting that those responses are consistent with the expected QBO-induced mean meridional circulation (e.g., Plumb and Bell 1982). Note that the divergence signal of E–P flux is shown around 20–70°S and 2–20 hPa (Fig. 4i), which corresponds to the westerly acceleration by the
planetary waves and is related to the equatorward flow signal of meridional circulation. Thus, the influences of the planetary waves are not ruled out. Consistent with the downward flow signal around 2–10 hPa and the upward flow signal around 20–50 hPa at 20–50°S, high-temperature signal is observed around 2–10 hPa and low-temperature signal around 20–50 hPa at the same latitude ranges. By the thermal wind relationship, these temperature signals should be related to the easterly wind signal around 1 hPa and the westerly wind signal around 10–20 hPa in the SH mid-latitudes (40–60°S) (Fig. 4a).

The previous paragraph described the westerly wind signal around 1–5 hPa, 40–60°S in July. We next describe the temporal behaviors of the westerly wind signal over the SH from SH midwinter to spring. The westerly wind signal around 1–5 hPa, 40–60°S in July is located on the equatorward side of the polar jet axis, meaning that the polar vortex prefers to shift equatorward under QBO-W condition as compared to QBO-E condition in July. In general, planetary waves propagate upward from the troposphere into the stratosphere during the SH winter and spring (e.g., Charney and Drazin 1961). These planetary waves are refracted away from the strong polar vortex in July. In other words, climatological E–P flux is upward from the extratropical troposphere into the stratosphere and upward/equatorward in the stratosphere in July. Thus, the equatorward shift of the polar vortex in the QBO-W condition corresponds to suppression of the climatological wave propagation route toward the equatorial upper stratosphere, with a southward/downward signal of the E–P flux at around 40–60°S and 10–100 hPa (Fig. 4i), thereby indicating the suppression of climatological planetary wave (WN1–3).
propagation in the QBO-W condition. This downward signal corresponds to the E–P flux divergence signal (westerly acceleration due to the suppression of, e.g., wave dissipation) in the mid- and high latitudes in the stratosphere around 20–70°S and 2–20 hPa in July (Fig. 4i). The area of westerly wind signal around 1–2 hPa, 40–60°S in July moves southward and downward from July to October (Figs. 4a–4d), and the center of this signal is always located over the upward/equatorward area of the PNJ core. Note that the timing of the shift-down of the PNJ in the QBO-W condition is later than that in the QBO-E condition. This monthly shift of $\beta_a$ (Figs. 4a–4d) is consistent with the monthly southward movement of the westerly signal (Fig. 2a). As shown in Figures 4i–4l and 6a, the area of downward E–P flux at around 40–80°S and 10–100 hPa itself moves downward from July to October due to the equatorward shift of the PNJ in QBO-W as the slowing of the shift-down of the PNJ (Figs. 4a–4d). This downward movement of the area of downward E–P flux corresponds to that of the E–P flux divergence signal in the stratosphere averaged over 40–80°S (Fig. 6a). Note that the E–P flux for WN1–3 largely (more than 80%) accounts for the net E–P flux derived from the total wavenumbers (not shown).

The divergence area is related to the upward circulation signal around 50–80°S and downward circulation signal around 20–40°S at 2–10 hPa in July and August (Figs. 4e and 4f). The upward circulation signal is widespread, from Antarctic (50–90°S) to the midlatitudes (20–40°S) at 2–200 hPa in September–October (Figs. 4g and 4h), as the divergence area is widespread, from 90°S to 40°S in the upper stratosphere, with the seasonal evolution of the PNJ. Via adiabatic
cooling, this upward circulation signal might be responsible for the low-temperature signal over the Antarctic region around 2–50 hPa in September, and around 50–90°S and 10–100 hPa in October (Figs. 4g and 4h).

3.4 *Lower QBO westerly effects on the SH polar-night jet*

To investigate the features of the seasonality and spatial distribution of the QBOb signal, we analyzed the latitude–height sections of the monthly mean QBOb signals. Figure 5 shows the latitude–height sections of regression coefficients $\beta_b$ of zonal-mean zonal wind, temperature, residual mean meridional circulation, and the zonal wavenumber 1–3 (WN1–3) components of E–P flux with its divergence. A westerly wind signal is seen at mid-latitudes (30–50°S) around 5 hPa in the upper stratosphere in July (Fig. 5a), which is located in the equatorward area of the PNJ core. In August, this westerly wind signal has become ill-defined in the upper stratosphere at 5–10 hPa around 40°S (Fig. 5b), accompanying the deepening of the easterly wind signal at 2–100 hPa around 60°S. These signals correspond to the convergence signal of the E–P flux around 5–10 hPa, 20–60°S (Fig. 5i). In September, two weak westerly wind signals appear separately again at 1 hPa near 60°S and at 10 hPa around 30°S (Fig. 5c). These two westerly signals merge into a single large, strong signal at the extratropics in the upper stratosphere, centered on the upward/equatorward area of the PNJ core in October (Fig. 5d), suggesting that the shift-down of the PNJ in the QBO-W condition occurs later than that in the QBO-E condition in October.
We also examined meridional circulation. In July, we observed a southward signal at 2–10 hPa, an equatorward signal at 30–50 hPa, and a southward signal near 100 hPa in the tropics with downward signal at 20–50°S around 10–20 hPa (Fig. 5e). These QBO-induced meridional flows are observable from July to October, with the high-temperature signal associated with adiabatic heating (Figs. 5e–5h). However, the downward signal of the meridional circulation at 20–50°S around 10–20 hPa is weakened in August, with temperature signal (maximum about 0.5 K) approximately half that in July (maximum about 1 K), or rather the meridional circulation is extended from 40°S to 80°S around 5–10 hPa in August, indicating the downward signal over the SH high-latitudes with the high-temperature signal there (Fig. 5f). This suggests that the behavior of the QBO-induced meridional circulation (i.e., two-cell structure) alone cannot explain this weakening of the westerly wind signal in August. Upward signals of the E–P flux, in relation to enhanced wave propagation from troposphere into stratosphere, are seen around 40–80°S at 10–200 hPa with the convergence signal in the stratosphere in August (Figs. 5j and 6b). These E–P flux signal for WN1–3 largely account for the E–P flux signal for the total wavenumbers (not shown). The convergence signal of the E–P flux could induce the extended meridional circulation signal from the equator to 80°S around 5–10 hPa in August with the weakening of the QBOb westerly wind signal around 40°S at 5–10 hPa and the deepening of the easterly wind signal at 2–100 hPa around 60°S. With the increasing magnitude of the upper stratospheric westerly wind signal around 60°S from September to October (Fig. 5c and 5d), the wave activity around 60°S becomes refracted away from the strong westerly wind of the
polar vortex, indicating the downward signal of the E–P flux at 10–100 hPa with the divergence signal (e.g., less dissipation of the planetary waves) in October (Fig. 5l).

Since wave propagation from troposphere into stratosphere in the QBO-W is enhanced during August and is related to the convergence signal of the E–P flux around the PNJ (Figs. 5i and 6a), the planetary waves influence the weakening of the westerly wind signal in the equatorward area of the PNJ core in August (Fig. 5a). The enhancement of planetary wave propagation from troposphere to stratosphere could be controlled by the strong stratospheric wind, as well as enhancement of the source of tropospheric wave activity. In future work, the behavior of tropospheric waves associated with the QBO will be investigated using both observations and numerical modeling, to identify the relative importance of the strong stratospheric wind and the tropospheric wave source.

4. Summary

The mechanism by which the QBO modulates extratropical circulation over the SH is poorly understood, as the various studies employed different height levels and metrics to define the phase of the QBO. In this study, we examined the response of atmospheric circulation over the SH to the stratospheric QBO westerly, defined by the equatorial zonal wind phases at middle- and lower-stratospheric levels. Previous studies employed composite analysis that possibly includes signals other than the response to the stratospheric QBO. In this study, multiple linear regression analysis of the EESC, two orthogonal QBO components, ENSO, and the volcanic
aerosol terms was conducted using the JRA-55 Reanalysis data set over a 51-year period from 1960 to 2010. Defining two orthogonal QBO component, the first two PCs (QBOa and QBOb signals) of the equatorial zonal wind were used for the QBO-related signals derived from these two PCs analyses. These QBOa and QBOb signals correspond to the middle- and lower-stratosphere QBO westerly responses, respectively. From SH spring to early summer, the effects of the middle-stratospheric QBO are dominant, whereas the effects of ENSO are dominant in SH early- to mid-winter.

The seasonal evolution of the climatological SH polar vortex indicates poleward and downward movement of its central position (shift-down) from SH late winter (August) to spring (September–November), as shown in previous studies. We suggest possible pathways of the QBO response in the polar vortex evolution at these middle- and lower-stratospheric levels.

In association with the middle-stratospheric QBO at 10–20 hPa (QBOa), the shift-down of the polar vortex in the QBO-W condition occurs later than that in the QBO-E condition from SH late winter to spring. This is associated with the westerly wind signal over the equatorward/upward area of the PNJ core in the SH mid-latitudes in the upper stratosphere. This westerly wind signal is consistent with the high-temperature anomaly in the SH low latitudes, synchronized with the QBO-induced mean meridional circulation that occurs from July to October. The delay in the shift-down of the strong polar vortex corresponds to the suppression of planetary wave propagation from the troposphere into the stratosphere.

The shift-down of the polar vortex in the lower-stratospheric QBO-W condition at 30–50 hPa
(QBOb) is also more delayed than that in QBO-E condition in SH spring, and the QBO-induced mean meridional circulation is also seen from July to October. In contrast to the QBOa, the westerly wind response of the SH polar vortex to the lower stratospheric QBO is unclear in August. This corresponds to the enhanced planetary wave propagation from the troposphere to the stratosphere in August.

Note that the diagnostic study in this work cannot establish firm conclusion, but hypotheses can be drawn about the roles of QBO influences. Hence, these results suggest that there are two possible pathways of stratospheric response to the QBO in terms of the seasonal evolution:

one possible pathway is that the middle-stratospheric QBO modifies the distributions of air temperature related to zonal wind and planetary wave activities, and meridional circulation in the low latitudes. This favours delayed evolution of the PNJ at high latitudes (around 60°S) from late winter (August) to spring (September–November) during the westerly phase of the middle-stratospheric QBO, consequently tending to strengthen westerly winds from stratosphere to troposphere in spring. Lower-stratospheric QBO is also related to temperature in low latitudes and zonal wind in low- and mid-latitudes in the stratosphere. The other possible pathway involves an increase in upward propagation of planetary waves from the mid- and high-latitudes troposphere to stratosphere in August responded to the westerly phase of the lower-stratospheric QBO, which is consistent with weakening of the PNJ. The numerical models that include the internal QBO and the relationship between the QBO and the polar vortex will be useful to clarify the two possible pathways of stratospheric response to the QBO.
Acknowledgments

The authors thank anonymous reviewers for their helpful comments and Dr. H. Akiyoshi of the National Institute for Environmental Studies, Japan, for many helpful discussions and comments. This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP16K16186 and JP18K03748. The datasets used for this study were provided from the Japanese 55-year Reanalysis (JRA-55) project conducted by the Japan Meteorological Agency (JMA), and the data set can be accessed via the JMA website (http://jra.kishou.go.jp/). Generic Mapping Tools (GMT) and Grid Analysis and Display System (GrADS) were used to draw the figures.
References


Hio, Y., and S. Yoden, 2005: Interannual variations of the seasonal march in the southern hemisphere


Figure legends

Figure 1. (a) Climatological seasonal evolution of 10 hPa daily zonal-mean zonal wind at 60°S for the period 1960–2010 (solid line), showing one standard deviation of interannual variability (shaded); (b) Latitude–height section of climatological seasonal evolution of polar-night jet (PNJ) axis position (circles) from 1 August to 31 December (the first day of each month is shown as a cross), together with its maximum wind speed (colored).

Figure 2. Latitude–time section of: (a) QBOa (β_a), and (b) QBOb (β_b) coefficients (black lines: m s⁻¹ per one standard deviation of the index terms) of the regression equation at 10 hPa, together with the 1σ and 2σ statistical significances (light and dark shading). Green lines indicate climatological zonal-mean zonal wind at 10 hPa for the period 1960–2010. Contour interval is 10 m s⁻¹ (solid lines: zero line and positive values; broken lines: negative values).

Figure 3. As in Fig. 2, but for the latitude–height section of: (a) QBOa, and (b) QBOb coefficients (m s⁻¹ per one standard deviation of the index terms) in November, together with climatology (green lines).

Figure 4. (a–d) As in Fig. 3, but for QBOa coefficients of zonal wind in June, July, August, September, and October, together with climatology; (e–h) As in (a–d), but for coefficients of temperature (contour: K), residual mean meridional circulation (vector: m s⁻¹), together with the 1σ and 2σ statistical significances of temperature (shading). The units are per one standard deviation of the index terms. Residual circulation vectors below 100-hPa level are multiplied by 0.3; (i–l) As in (a–d), but for zonal wavenumber 1–3 (WN1–3) components of the E–P flux (vector: kg m⁻¹ s⁻²) and its divergence (contour: m s⁻¹ d⁻¹). E–P flux vectors below 100-hPa level are multiplied by 0.1. The vertical components of E–P flux and residual circulation are magnified ×100 relative to the horizontal component; scales for the horizontal vector are shown at the bottom-right of the panel.

Figure 5. As in Fig. 4, but for QBOb coefficients.

Figure 6. Time–height section of: (a) QBOa (β_a), and (b) QBOb (β_b) coefficients of the vertical E–P flux for the WN1–3 component averaged over 40–80°S (black lines: ×10⁻³ kg m⁻¹ s⁻² per one standard deviation of the index terms), together with the E–P flux divergence, shown as red (positive) and blue (negative) (shaded: m s⁻¹ d⁻¹).
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.14±0.16</td>
<td>0.15±0.19</td>
<td>-0.10±0.21</td>
<td>-0.33±0.21</td>
<td>0.21±0.23</td>
<td>1.25±0.23</td>
<td>1.60±0.18</td>
</tr>
<tr>
<td>$\beta_a$</td>
<td>-0.11±0.17</td>
<td>0.12±0.20</td>
<td>0.17±0.22</td>
<td>0.42±0.22</td>
<td>0.89±0.25</td>
<td>1.01±0.25</td>
<td>0.56±0.19</td>
</tr>
<tr>
<td>$\beta_b$</td>
<td>-0.30±0.17</td>
<td>-0.26±0.18</td>
<td>-0.21±0.19</td>
<td>-0.17±0.18</td>
<td>0.12±0.20</td>
<td>0.56±0.22</td>
<td>0.63±0.18</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.15±0.17</td>
<td>0.20±0.20</td>
<td>0.06±0.21</td>
<td>-0.10±0.20</td>
<td>-0.18±0.22</td>
<td>-0.20±0.22</td>
<td>-0.13±0.17</td>
</tr>
<tr>
<td>$\delta$</td>
<td>-0.33±0.25</td>
<td>-0.24±0.26</td>
<td>0.04±0.25</td>
<td>0.19±0.21</td>
<td>0.02±0.21</td>
<td>-0.25±0.21</td>
<td>-0.32±0.16</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>-0.02±0.17</td>
<td>0.06±0.20</td>
<td>0.23±0.21</td>
<td>0.22±0.20</td>
<td>-0.05±0.22</td>
<td>-0.35±0.23</td>
<td>-0.40±0.18</td>
</tr>
</tbody>
</table>

Table 1. Monthly values and 1σ errors of regression coefficients in the linear regression equation for zonal-mean zonal wind averaged over 40–80°S, 1–200 hPa. Units for $\alpha$, $\beta_a$, $\beta_b$, $\gamma$, $\delta$, and $\epsilon$ are m s$^{-1}$ per one standard deviation of the index terms. The bold indicates that the statistical fits are significantly different from zero at the 1σ level.
JRA-55 10 hPa Zonal Wind

(a) QBOa

(b) QBOb
JRA-55 Zonal Wind

(a) QBOa in Nov.

(b) QBOb in Nov.
JRA-55 QBOa coefs.

(a) Jul. U  (e) Jul. T, ($\vec{v}^*, \vec{w}^*$)  (i) Jul. WN1–3
(b) Aug. U  (f) Aug. T, ($\vec{v}^*, \vec{w}^*$)  (j) Aug. WN1–3
(c) Sep. U  (g) Sep. T, ($\vec{v}^*, \vec{w}^*$)  (k) Sep. WN1–3
(d) Oct. U  (h) Oct. T, ($\vec{v}^*, \vec{w}^*$)  (l) Oct. WN1–3
JRA-55 QBOb coefs.

(a) Jul. U  
(b) Aug. U  
(c) Sep. U  
(d) Oct. U  
(e) Jul. T, (\(\vec{v}^*, \vec{w}^*\))  
(f) Aug. T, (\(\vec{v}^*, \vec{w}^*\))  
(g) Sep. T, (\(\vec{v}^*, \vec{w}^*\))  
(h) Oct. T, (\(\vec{v}^*, \vec{w}^*\))  
(i) Jul. WN1–3  
(j) Aug. WN1–3  
(k) Sep. WN1–3  
(l) Oct. WN1–3
JRA-55 Fz & EPF Div.

(a) QBOa

(b) QBOb