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Key Points:
- The North Pacific storm track shifts poleward in easterly QBO winters likely in response to the changes in eddy refraction and baroclinicity
- The North Atlantic storm track shrinks (expands) vertically in easterly (westerly) QBO winters in accordance with the tropopause height variation

Supporting Information:
- Supporting Information S1

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Interannual Modulation of Northern Hemisphere Winter Storm Tracks by the QBO

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Abstract Storm tracks, defined as the preferred regions of extratropical synoptic-scale disturbances, have remarkable impacts on global weather and climate systems. Causes of interannual storm track variation have been investigated mostly from a troposphere perspective. As shown in this study, Northern Hemisphere winter storm tracks are significantly modulated by the tropical stratosphere through the quasi-biennial oscillation (QBO). The North Pacific storm track shifts poleward during the easterly QBO winters associated with a dipole change in the eddy refraction and baroclinicity. The North Atlantic storm track varies vertically with a downward shrinking (upward expansion) in easterly (westerly) QBO winters associated with the change of the tropopause height. These results not only fill the knowledge gap of QBO-storm track relationship but also suggest a potential route to improve the seasonal prediction of extratropical storm activities owing to the high predictability of the QBO.

Plain Language Summary Storm tracks are regions in which the midlatitude cyclones are most prevalent. Midlatitude cyclones can cause extreme precipitation and heat/cold events over North America and Europe. Therefore, having a better understanding of how storm tracks change may help in predicting potential natural disasters. Previous studies have shown that storm tracks change from year to year as a result of tropospheric or polar stratospheric variabilities. By examining reanalysis data, we find that change in tropical stratospheric wind direction modulates significant year-to-year variation of storm tracks. In the North Pacific, the storm track shifts poleward with the easterly wind in the tropical stratosphere, while in the North Atlantic, the storm track shrinks (expands) vertically with the easterly (westerly) wind in the tropical stratosphere. These changes are associated with changes in atmospheric instability modulated by the stratospheric wind. Our findings offer an opportunity to improve seasonal forecasts of storm tracks and their extreme impacts by taking the stratospheric variability into account as a source of predictability.

1. Introduction

Storm tracks are defined as the prevalent regions of extratropical synoptic-scale disturbances with the climatological maxima located over the North Pacific and the North Atlantic, respectively, in the Northern Hemisphere (e.g., Blackmon, 1976). They exhibit significant interannual variation including fluctuation of the intensity and shift in location (e.g., Lau, 1988). Because of the substantial impacts of storm tracks on global weather and climate systems (e.g., Chang et al., 2016; Kunkel et al., 2012; Luo et al., 2011; Salathé, 2006), causes for their interannual variation have been extensively studied (e.g., review by Chang et al., 2002). In the North Pacific, the meridional shift of the storm track can be modulated by the El Niño–Southern Oscillation (ENSO). An equatorward shift and eastward extension of the storm track has been observed during El Niño winters, and vice versa during La Niña winters (Straus & Shukla, 1997; Trenberth & Hurrell, 1994; Wang et al., 2017). In the North Atlantic, the North Atlantic Oscillation is known as the dominant contributor to the interannual variation of the storm track (Bader et al., 2011; Burkhardt & James, 2006; Chang, 2009). Links between storm track variations and the stratospheric polar vortex have also been found (e.g., Kidston et al., 2015; Shaw et al., 2016). However, to date, less attention has been paid to the impacts of tropical stratospheric variability such as the quasi-biennial oscillation (QBO) on storm track variation.

The QBO is a pronounced interannual phenomenon in the stratosphere characterized by a continuous oscillation of equatorial zonal wind (Baldwin et al., 2001). It influences weather and climate phenomena not only in the stratosphere (e.g., Garfinkel & Hartmann, 2007; Watson & Gray, 2014) but also in the troposphere. Tropical cyclones (Camargo & Sobel, 2010; Ho et al., 2009), ENSO (Gray et al., 1992a, 1992b), the Madden-Julian Oscillation (Son et al., 2017; Yoo & Son, 2016), and the North Atlantic Oscillation (Peings et al., 2013) have all been found to be highly influenced by the QBO. Although the linkage between the QBO and the tropospheric variability has been documented, there has been little work on the QBO's impact on storm tracks. According to Garfinkel and Hartmann (2011a, 2011b), extratropical zonal wind anomalies associated with the QBO can extend from the stratosphere to the troposphere. Given that variation of the subtropical jet is associated with variation in storm tracks, an influence of the QBO on storm tracks is thus implied. On the other hand, the QBO can modulate the tropopause height not only in the tropics but also in the extratropics (Huesmann & Hitchman, 2001). This alludes to another possible pathway of the QBO influence on storm tracks owing to the fact that a tropopause height change can lead to a vertical variation in storm tracks (Lorenz & DeWeaver, 2007; Yin, 2005).

In this study, we aim to explore the interannual modulation of the QBO on storm tracks and its underlying mechanisms with a specific focus on boreal winter (October to March) during the period of 1979–2016. As will be shown, the North Pacific and North Atlantic storm tracks (NPST and NAST) show remarkably different responses to the QBO. The plausible mechanisms of the QBO-related storm track changes are explained by changes in baroclinicity, eddy refraction, and tropopause height.

2. Data and Method

The European Centre for Medium-Range Weather Forecasts Interim reanalysis data set (Dee et al., 2011) is used in the present study. Specifically, daily averaged and monthly pressure-level data are used including horizontal winds, air temperature, and vertical velocity with a horizontal resolution of 2.5° longitude × 2.5° latitude and a vertical resolution of 50 hPa in the troposphere and 10 hPa in the stratosphere. Surface quantities, such as sea level pressure and surface pressure, are also used. To investigate the QBO impact on the tropopause height, monthly tropopause pressure is obtained from the National Centers for Environmental Prediction/National Centre for Atmospheric Research Reanalysis 1 (Kalnay et al., 1996).

The Extended Reconstructed Sea Surface Temperature, version 4 (Huang et al., 2015) provided by the National Oceanic and Atmospheric Administration is used to determine ENSO phases. El Niño events are defined by the boreal winter-mean Niño-3.4 index larger than 0.6 K (= 0.8 standard deviation), while La Niña events correspond to the Niño-3.4 index less than −0.6 K. Out of 37 winters, 12 El Niño events and 12 La Niña events are selected.

Different phases of the QBO are determined by normalized tropical-mean (10°S–10°N) 50 hPa zonal wind anomalies (U50). If the boreal winter-mean U50 is larger than 0.8 standard deviation, the corresponding winter is regarded to be in the westerly phase of the QBO (WQBO). Likewise, if U50 is smaller than −0.8 standard deviation, the corresponding winter is treated as an easterly QBO (EQBO) winter (similar to Yoo & Son, 2016 and Son et al., 2017). Based on this criterion, 12 out of 37 winters are selected as WQBO winters and 10 as EQBO winters. In the 10 EQBO winters, there are 4 La Niña events but no El Niño events, while in the 12 WQBO winters, La Niña and El Niño events each take up 4 winters.

Eddy kinetic energy (EKE) is used to identify storm tracks (Deng & Jiang, 2011; Takahashi & Shirooka, 2014; Wang et al., 2017). It is expressed as

$$\mathrm{EKE} = \frac{1}{2}\left(u'^2 + v'^2\right) \tag{1}$$

where u and v are the zonal and meridional wind, respectively, and prime indicates the synoptic-scale variability filtered by a 2–8 day band-pass Lanczos filter (Duchon, 1979). Anomalies of all variables are derived by subtracting their daily climatology from the total field.

3. Results

3.1. Seasonal Mean Flow and Storm Track Changes Associated With the QBO

To examine the QBO impact on changes in the seasonal mean flow, vertical structures of zonal wind anomalies in the troposphere corresponding to the different QBO phases are compared. The area-averaged results over the North Pacific (130°E–120°W) and the North Atlantic (90°W–0°) basin are displayed in Figure 1. The areas are chosen based on the climatological centers of storm tracks (Figure S1 in the supporting information). This basin average will be applied to all the results of this study. Significant changes in the zonal wind are observed especially in the North Pacific (Figure 1). Compared to the climatology, there is a poleward shift in the North Pacific westerly jet in EQBO winters (Figure 1a) and an equatorward shift in WQBO winters

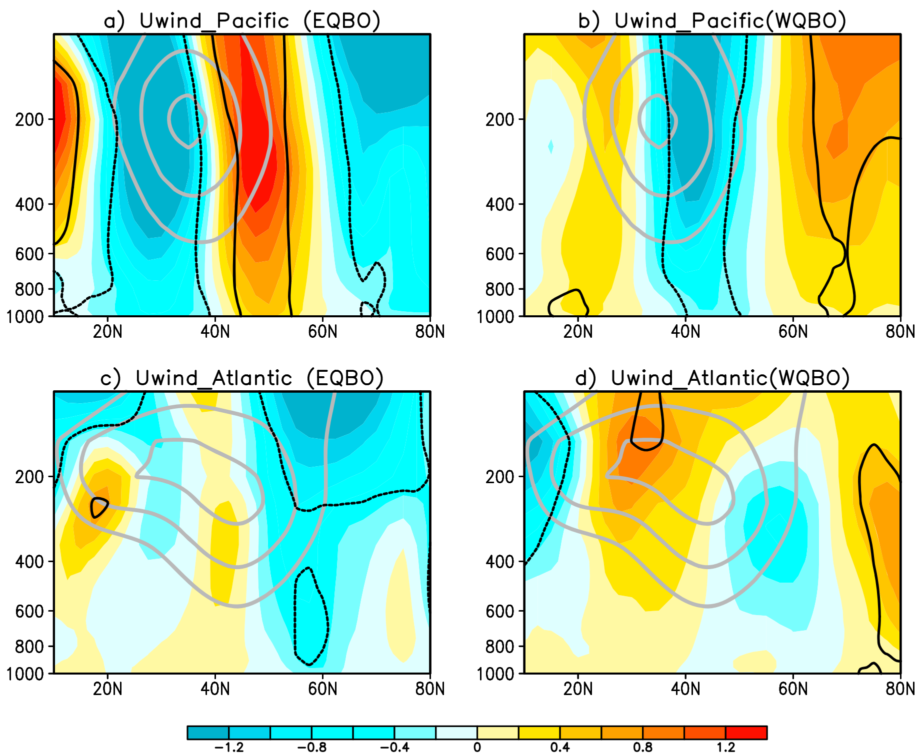

Figure 1. Latitude-pressure cross section of (upper) Pacific-averaged (130°E–120°W) and (lower) Atlantic-averaged (90°W–0°) zonal wind anomalies (shading; m s^{-1}) in (left) easterly phase of the quasi-biennial oscillation (EQBO) winters and (right) westerly phase of the quasi-biennial oscillation (WQBO) winters. Gray contours indicate the climatology of the westerly jet (interval: 10 m s^{-1} for the North Pacific and 5 m s^{-1} for the North Atlantic; values lower than 10 m s^{-1} are omitted). Black contours indicate the 95% confidence level according to the Student's *t* test.

(Figure 1b). This is consistent with the results of Garfinkel and Hartmann (2011a, 2011b), who attributed this meridional jet shift to the changes in the tropospheric eddy activities.

In the North Atlantic (Figures 1c and 1d), the change in the westerly jet is less symmetric between the two QBO phases and is remarkably different from that in the North Pacific. During EQBO winters (Figure 1c), a significant weakening is seen on the northern flank of the jet, while in WQBO winters (Figure 1d), an overall strengthening of the jet with the maximum near the tropopause is discerned.

Interannual changes in storm tracks (defined by EKE) corresponding to the different QBO phases are compared in Figure 2. In the North Pacific, unlike the symmetric changes in zonal wind (i.e., a poleward (equatorward) shift of the jet stream in EQBO (WQBO) winters; Figures 1a and 1b), the NPST exhibits a significant poleward shift during EQBO winters (Figure 2a) but an upward extension during WQBO winters (Figure 2b). Although at 400 hPa and below, an equatorward shift of the NPST is discerned during WQBO winters (Figures 2b and S1b) which is roughly consistent with the change of the jet (Figure 1b), this shift is not statistically significant and hence will not be the focus in this study. In the North Atlantic (Figures 2c and 2d), a systematic downward shrinking (upward expansion) of the NAST is seen in EQBO (WQBO) winters. In this sense, there are large dissimilarities of QBO modulation on storm tracks between the two basins.

To test the robustness of the results, two other metrics that have widely been used to define storm tracks, vv300 (Chang, Guo, & Xia, 2012; Chang & Yau, 2016; Wallace et al., 1988) and pp (Chang et al., 2012; Chang & Yau, 2016), are compared in the supporting information (Text S1 and Figure S1). The 950–250 hPa averaged EKE anomalies are shown together in Figure S1. It is found that the poleward shift of the NPST in EQBO winters is quite robust that all the three metrics produce well this change. When comparing vv300 (at 300 hPa) and pp (at sea level) with EKE (Figure 2) at the same pressure level, they indicate identical storm track variation (figure not shown).

As suggested by Nishimoto and Yoden (2017), there may be an asymmetric relationship between the QBO and ENSO. More La Niña events are likely to occur in EQBO winters, while there is no significant preference

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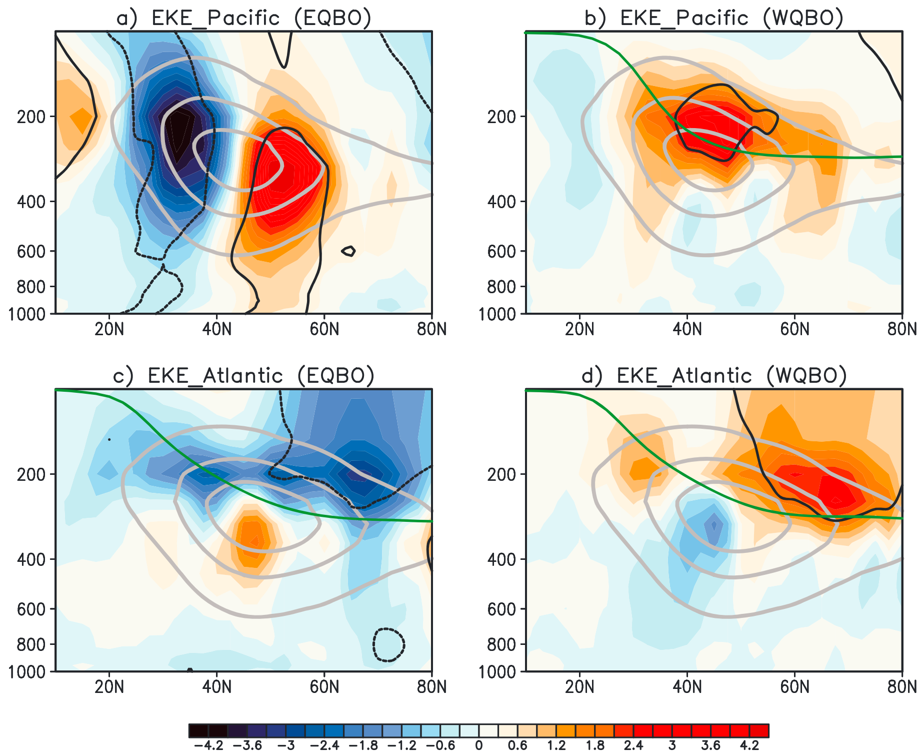

Figure 2. Same as Figure 1, except for the eddy kinetic energy (EKE) anomalies (shading; $m^2\ s^{-2}$). Gray contours indicate the climatology of storm tracks (interval: 30 $m^2\ s^{-2}$). Green lines indicate the tropopause height (pressure). Black contours represent the 95% confidence level according to the Student's *t* test. EQBO = easterly phase of the quasi-biennial oscillation; WQBO = westerly phase of the quasi-biennial oscillation.

for specific ENSO events in WQBO winters (Figure S2). Because La Niña events can result in a poleward shift of the NPST (Straus & Shukla, 1997; Trenberth & Hurrell, 1994; Wang et al., 2017), one may argue that the variation of the NPST in EQBO winters may be dominated by La Niña. To test this possibility, we discarded EQBO winters that have significant La Niña events (4 discarded from 10 winters). The result (Figure S3) shows that in neutral ENSO winters, a poleward shift of the NPST is still recognizable in EQBO phase albeit with changes in the amplitude. Therefore, we can conclude that the storm track change caused by the EQBO is not strongly influenced by ENSO.

3.2. Plausible Mechanisms

3.2.1. The Poleward Shift of the NPST in EQBO Winters

In this section, mechanism of the poleward shift of the NPST during EQBO winters is discussed. The upward expansion of the NPST in WQBO winters will be discussed later along with the NAST because of their similar responses to the QBO. The poleward shift of the NPST is reminiscent of the change in the westerly jet (Figure 1a) which is indicative of a change in baroclinicity. Because the genesis of midlatitude storms is largely controlled by baroclinic instability (Eady, 1949), change in the baroclinicity will, therefore, influence the storm track. To test this hypothesis, the climatological baroclinicity over the North Pacific and its change in EQBO winters are displayed in Figure 3a. Here the baroclinicity is defined as the product of the inverted Brunt-Väisälä frequency (N) and the negative meridional temperature gradient, $-N^{-1}\frac{dT}{dy}$, averaged from 950 to 250 hPa. The climatology of the baroclinicity is positive at all latitudes, indicating a negative meridional temperature gradient as expected. In EQBO winters, a significant increase of baroclinicity to the north (40°–60°N) and a decrease to the south (20°–35°N) of the climatological NPST match the observed poleward shift of the NPST (Figure 2a). This supports the hypothesis that the change in the baroclinicity is an important contributor to the change in the NPST during EQBO winters.

Besides the baroclinicity change, Garfinkel and Hartmann (2011a, 2011b) and Lu et al. (2014) suggested that the QBO-related zonal wind change can also lead to a change in the refractive index (n^2). This change in n^2 will influence the eddy propagation because waves tend to propagate toward (away from) positive (negative)

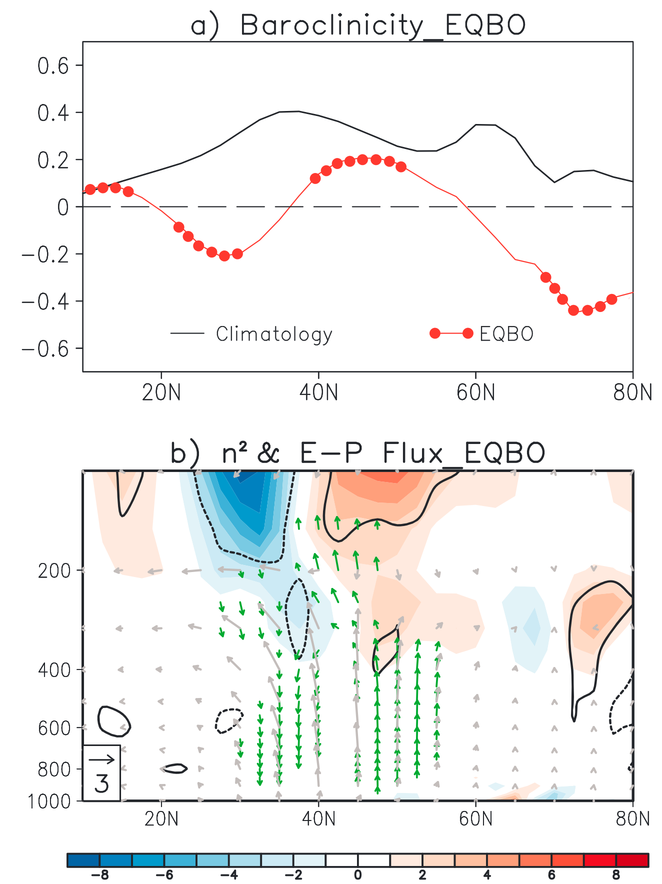

Figure 3. a Climatology of Pacific-averaged (130°E–120°W) baroclinicity (black line; 10^6 K s m^{-1}) and corresponding anomalies in easterly phase of the quasi-biennial oscillation (EQBO) winters (red line with filled circle; 2×10^7 K s m^{-1}). The baroclinicity is defined as $-N^{-1}\frac{dT}{dy}$ averaged from 950 to 250 hPa. Anomalies exceeding the 95% confidence level are dotted. (b) Latitude-pressure cross section of Pacific-averaged refractive index (n^2, shading) and Eliassen-Palm (E-P) flux (green vectors) anomalies in EQBO winters. Only significant vectors exceeding the 95% confidence level are shown. Gray vectors indicate the climatology of the E-P flux (the original values are divided by 10). The E-P flux is scaled as in Edmon et al. (1980) for the visualization purpose. Black contours represent the 95% confidence level for n^2 according to the Student's t test.

n^2 (Andrews et al., 1987; Karoly & Hoskins, 1982). Given that vertical eddy propagation is determined by storm track-related eddy fluxes, this suggests a possible role of eddy refraction in the NPST variation.

To examine this possibility, n^2 is computed based on the following formula (e.g., Matsuno, 1970; Simpson et al., 2009):

$$n^2 = \left[\frac{q_\varphi}{a(u-c)} - \left(\frac{k}{a\cos\varphi}\right)^2 - \left(\frac{f}{2NH}\right)^2\right]a^2 \tag{2}$$

where q_φ is the meridional gradient of potential vorticity, c is the zonal phase speed (7 m s^{-1}), k is the zonal wavenumber 5, N is the Brunt-Väisälä frequency, H is the scale height, and a is the Earth radius (6,371 km). Eddy propagation is examined by calculating Eliassen-Palm (E-P) flux which is expressed as $[0, -a\cos\varphi\left(\overline{u'v'}\right), af\cos\varphi\left(\overline{v'\theta'}\right)/\overline{\theta}_z]$. The meridional component of the E-P flux represents the meridional momentum flux ($\overline{u'v'}$), and the vertical component denotes the meridional heat flux ($\sim\overline{v'T'}$) (Gavrilov et al., 2015; Vallis, 2017). Note that an anomalous upward eddy propagation (i.e., a positive $\overline{v'T'}$ anomaly) is indicative of an enhancement of the storm track, and vice versa for a downward eddy propagation.

The anomalies of n^2 and E-P flux over the North Pacific are shown in Figure 3b. A significant dipole change in n^2 is seen over 20°–60°N with a negative n^2 at the south and a positive n^2 at the north. According to the theory proposed by Karoly and Hoskins (1982) and Andrews et al. (1987), this dipole change is expected to be accompanied by an anomalous E-P flux directing toward (away from) the positive (negative) n^2. Indeed, a significant downward (upward) eddy propagation to the south (north) of the climatological NPST is seen, which matches the poleward shift of the NPST (Figure 2a). This supports the hypothesis that changes in the eddy refraction may also lead to the observed NPST variation during EQBO winters.

Although the dipole change in the baroclinicity and n^2 are important in the NPST variation, they may act as an amplifier rather than a trigger for the observed NPST shift. Garfinkel and Hartmann (2011a, 2011b) suggested that the mean flow change in the troposphere is realized by eddies via anomalous eddy momentum convergence. They thus pointed out a possible positive feedback between the mean flow and eddies: eddy flux convergence influenced by the QBO-related n^2 change leads to a poleward shift of the jet, which hence amplifies the changes in eddies.

3.2.2. The Vertical Expansion/Shrinking of the NAST and the NPST

In this section, a mechanism for the vertical expansion/shrinking of the NAST and the NPST under the QBO modulation is discussed. Note that changes in the NAST (Figures 2c and 2d) do not simply follow changes in the westerly jet (Figures 1c and 1d). The regions of significant changes in n^2 and eddy propagation do not coincide with each other as well (figure not shown). Therefore, the baroclinicity and eddy refraction may not be the main contributors to the observed NAST variation during the two different QBO phases. Rather, the vertical variation of the NAST is reminiscent of its relationship with the tropopause height variation. Based on zonal-mean results, Yin (2005) and Lorenz and DeWeaver (2007) pointed out that a lifting of the midlatitude tropopause may result in an upward expansion of the storm track and vice versa for a lower tropopause height. This is due to the fact that synoptic waves are trapped near the tropopause because of a sharp increase of static stability at the tropopause which gives rise to a sharp potential vorticity gradient on which these waves propagate (e.g., Hoskins et al., 1985). Therefore, a lifting (falling) of the tropopause leads to higher (lower) levels favorable of the storm track activities.

To examine the possible impact of the QBO on the midlatitude tropopause height, climatological tropopause pressure over the North Atlantic and its variation during the two QBO phases are shown in Figure 4a.

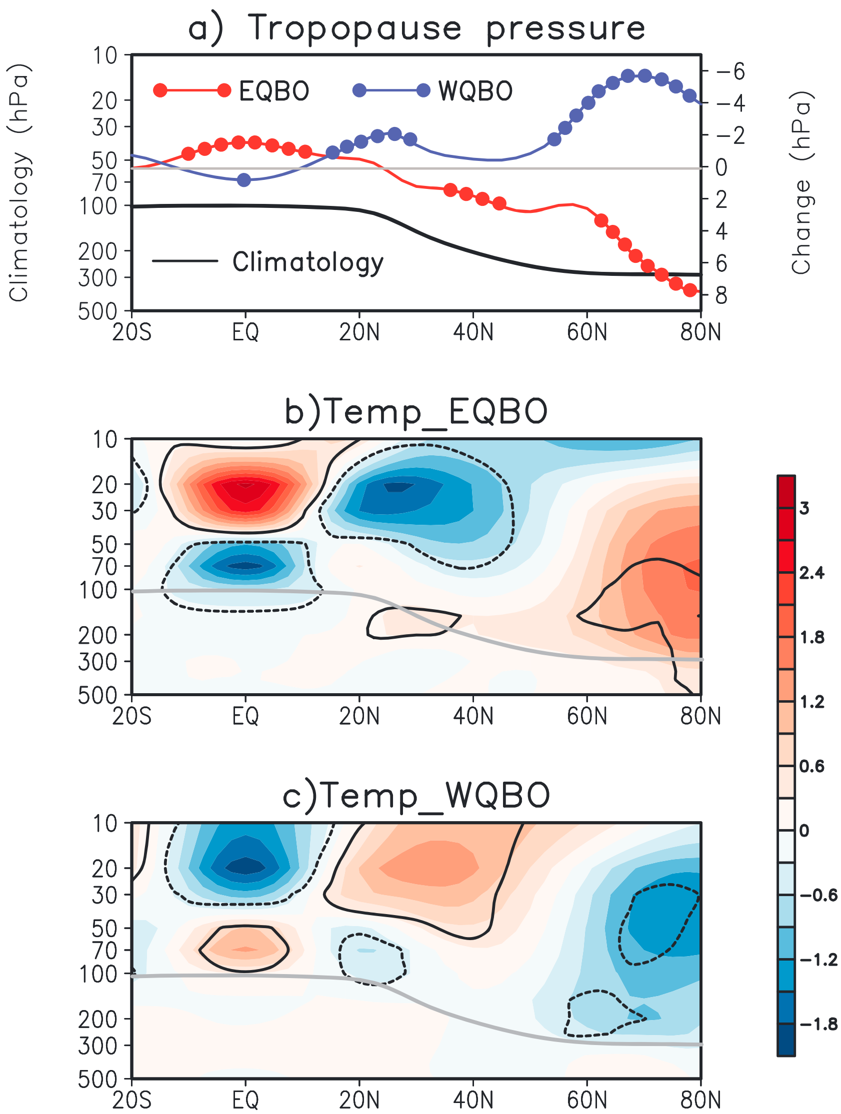

Figure 4. (a) Climatology of Atlantic-averaged (90°W–0°) tropopause pressure (black lines; hPa) and corresponding anomalies (colored lines) during the two different quasi-biennial oscillation (QBO) phases. The left *y* axis represents the climatological tropopause pressure, while the right *y* axis indicates the anomalies. A positive anomaly suggests a lower tropopause and vice versa for a negative anomaly. Anomalies exceeding the 95% confidence level are dotted. (b and c) Latitude-pressure cross section of Atlantic-averaged air temperature anomalies (shading; K) in (b) easterly phase of the QBO (EQBO) winters and (c) westerly phase of the QBO (WQBO) winters. Black contours indicate the 95% confidence level according to the Student's *t* test. Gray lines indicate the climatology of the tropopause pressure (same as the black line in (a)).

Climatologically, the tropopause is higher in the tropics and gradually decreases to the polar region. In EQBO (WQBO) winters, the tropopause is anomalously higher (lower) in the tropics and lower (higher) in the middle to high latitudes. The lower (higher) tropopause in the middle to high latitudes during EQBO (WQBO) winters matches the downward shrinking (upward expansion) of the NAST (Figures 2c and 2d). Note that changes in the tropopause height are most pronounced in the high latitude, which partly explains why the variation in the NAST is most significant north of its climatological maximum.

As suggested by Huesmann and Hitchman (2001), the QBO may influence the tropopause height by modulating the stratospheric temperature near the tropopause. To explain the observed changes in the tropopause height, the QBO-associated temperature anomalies from the middle troposphere to the lower stratosphere are compared between the two phases (Figures 4b and 4c). Generally, the significant changes in temperature are not limited to the equatorial stratosphere where the QBO occurs but extend to the troposphere and extratropical regions. When there is a significant warming in the stratosphere, the static stability in the region of the tropopause will increase, which implies a lower tropopause, and vice versa for a cooling in the stratosphere (Lorenz & DeWeaver, 2007). In EQBO winters, there is a significant warm temperature anomaly from 60° to 80°N above the climatological tropopause (~300 hPa) (Figure 4b). In response, a remarkable lower tropopause (red curve in Figure 4a) and the associated downward shrinking of the NAST (Figure 2c) is seen. On the other hand, the significant cooling anomaly from 55° to 80°N (Figure 4c) in WQBO winters results in the lifting of the tropopause (blue curve in Figure 4a) and hence the upward expansion of the NAST (Figure 2d). The results for the North Pacific are presented in Figure S4. In general, the upward expansion of the NPST during WQBO winters (Figure 2b) can also be explained by the lifting of the tropopause, although discrepancies with the North Atlantic are noticed (Text S2).

4. Summary and Discussion

This study examined the interannual modulation of Northern Hemisphere winter storm tracks by the QBO over the period 1979–2016. In general, the North Pacific and North Atlantic storm tracks respond differently to the QBO with different mechanisms. The NPST shifts poleward during EQBO winters, which is likely influenced by the variation in the jet stream (an indicator of changes in the baroclinicity) and eddy refraction. On the other hand, the NAST shrinks downward (expands upward) in EQBO (WQBO) winters in accordance with the decreased (raised) tropopause height (a manifestation of static stability changes). These results provide a new insight of the possible impact on storm tracks from one of the most significant low-frequency variations in the stratosphere. More importantly, this study suggests a potential route for the improvement of seasonal prediction of extratropical storm activities. In previous studies, ENSO has been primarily considered as the main source of seasonal storm track predictability. Yang et al. (2015) suggested that ENSO-related storm tracks are predictable at a lead time of 9 months. According to Scaife et al. (2014), the predictability of the QBO is effectively higher than that of ENSO (12 months versus 6–8 months) (Jin et al., 2008; Kirtman & Min, 2009). Therefore, it is anticipated that the seasonal prediction of storm tracks could be improved by taking the QBO into account.

Acknowledgments
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