Decadal Relationship between the Stratospheric Arctic Vortex and Pacific Decadal Oscillation

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ABSTRACT

Using reanalysis datasets and numerical simulations, the relationship between the stratospheric Arctic vortex (SAV) and the Pacific decadal oscillation (PDO) on decadal time scales was investigated. A significant in-phase relationship between the PDO and SAV on decadal time scales during 1950–2014 is found, that is, the North Pacific sea surface temperature (SST) cooling (warming) associated with the positive (negative) PDO phases is closely related to the strengthening (weakening) of the SAV. This decadal relationship between the North Pacific SST and SAV is different from their relationship on subdecadal time scales. Observational and modeling results both demonstrate that the decadal variation in the SAV is strongly affected by the North Pacific SSTs related to the PDO via modifying the upward propagation of planetary wavenumber-1 waves from the troposphere to the stratosphere. The decreased SSTs over the North Pacific tend to result in a deepened Aleutian low along with a strengthened jet stream over the North Pacific, which excites a weakened western Pacific pattern and a strengthened Pacific–North American pattern. These tropospheric circulation anomalies are in accordance with the decreased refractive index (RI) at middle and high latitudes in the northern stratosphere during the positive PDO phase. The increased RI at high latitudes in the upper troposphere impedes the planetary wavenumber-1 wave from propagating into the stratosphere, and in turn strengthens the SAV. The responses of the RI to the PDO are mainly contributions of the changes in the meridional gradient of the zonal-mean potential vorticity via alteration of the baroclinic term $f^2 \rho_0 (\rho_0 \nabla^2)$. 

1. Introduction

The stratospheric Arctic vortex (SAV) is critical to the stratosphere–troposphere exchange, and its evolution in response to global warming is important for the surface climate (e.g., Cohen et al. 2014; Kim et al. 2014). It is reported that the anomalously warm SAV may cause severely cold winters and frequent cold air outbreaks in the northern midlatitudes (e.g., Kolstad et al. 2010; Mitchell et al. 2013; Cohen et al. 2014; Zhang et al. 2016). Thus, understanding and predicting the SAV change is crucial to the improvement of the extended range forecasts (e.g., Baldwin et al. 2003; Kolstad and Charlton-Perez 2011; Roff et al. 2011). Recently, Garfinkel et al. (2017) noted that the decadal variability in the Eurasian surface air temperature may be directly affected by the decadal variability in the SAV.

El Niño–Southern Oscillation (ENSO) is the most important interannual climate mode in the tropics, and its impacts on the SAV have attracted a great deal of attention. Observational and modeling studies have noted that the polar vortex tends to be weaker and warmer during El Niño winters (e.g., Sassi et al. 2004; Garfinkel and Hartmann 2008; Xie et al. 2012). The nonlinearity and asymmetry of ENSO also has significant influences on the northern winter stratosphere (Rao and Ren 2016). Manzini et al. (2006) showed that ENSO can enhance the forcing and the vertical propagation of planetary waves into the stratosphere by altering the large-scale pattern in the extratropical troposphere. However, Hu et al. (2014) found that the SAV in response to the sea surface temperature (SST) meridional gradient is weaker than the response to the
uniform SST, which suggests that not only can the tropical SST anomalies (SSTAs) affect the SAV, but also that the extratropical SSTAs have important influences on the SAV.

Several recent studies have investigated the connections between the North Pacific and the extratropical stratosphere (e.g., Shi et al. 2017; Hu et al. 2018; Li et al. 2018) and the potential relationship between the Pacific decadal oscillation (PDO) and the SAV (Jadin et al. 2010; Hurwitz et al. 2012; Woo et al. 2015; Kren et al. 2016; Wang et al. 2016). The PDO, which is defined as the leading mode of SSTAs in the North Pacific poleward of 20°N (Mantua et al. 1997; Zhang et al. 1997), has important impacts on the northern climate; these impacts include the Pacific storm track (Lee et al. 2012), geopotential height anomalies over the North Pacific frontal zone (Taguchi et al. 2012), and the large-scale circulation (Woolings et al. 2010; Garfinkel et al. 2010). These tropospheric climate anomalies associated with the PDO can alter the wave activity in the stratosphere, which further affects the SAV. Jadin et al. (2010) have reported that the variations in the penetration of planetary waves from the troposphere into the stratosphere are strongly linked to the PDO in early winter. Recently, Woo et al. (2015) found that weak stratospheric polar vortex events occur more frequently during positive PDO phases than during negative PDO phases. Subsequently, using model simulations, Kren et al. (2016) further reported that the PDO positive phase is marked by a warmer northern polar stratosphere. These studies have made good progress in understanding the relationship between the PDO and SAV. However, these studies focused more on the responses of different PDO phases based on the original time series or a 5-yr running mean, which cannot clearly rule out the possible contamination of the PDO signal from ENSO. While the PDO has a distinct decadal variation, it also contains some random high-frequency variability. The numerical results of Hurwitz et al. (2012) have already shown that the relatively warmer North Pacific SSTs can lead to a less-disturbed seasonal mean SAV. However, besides the PDO mode, the North Pacific SSTs also have an additional mode known as the Victoria mode (Bond et al. 2003) or North Pacific Gyre Oscillation (Di Lorenzo et al. 2008) to describe the low-frequency variability of the North Pacific SSTs, which cannot be fully explained by the PDO alone. In addition, there has been a limited focus on the decadal relationship between the SAV and PDO using the observations.

The abovementioned studies suggested that the tropospheric circulation anomalies over the North Pacific in association with the positive (negative) PDO during boreal winters tend to result in more (less) planetary waves in the stratosphere by constructively (destructively) interfering with the climatological planetary waves (Hurwitz et al. 2012; Woo et al. 2015; Kren et al. 2016). However, some other studies have provided evidence that the increased SSTs can result in a larger meridional temperature gradient in the subtropical troposphere, which further increases the upper-tropospheric zonal winds following the thermal wind relationship, and hence leads to more vertically propagating waves being re-refracted poleward (e.g., Olsen et al. 2007; Shu et al. 2011; Hu et al. 2014). Therefore, it is still not well understood what roles the planetary wave propagation conditions around the extratropical tropopause play in the relationship between the PDO and SAV.

In this study, we investigate the decadal variation of the SAV and the influences of the decadal variation in the PDO on the SAV, as well as the underlying dynamical mechanism, by using long-term reanalysis datasets and a general circulation model. The paper is organized as follows: data, methods, and numerical experiments are presented in section 2. The decadal relationship between the PDO and SAV is analyzed in section 3. The possible mechanism for the PDO to influence SAV is elucidated in section 4. Finally, conclusions and discussion are given in section 5.

2. Data, methods, and numerical experiments

a. Datasets

First, we adopted the monthly temperature, horizontal winds, and geopotential height datasets from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NCEP1) during the period from 1950 to 2014, which has a horizontal resolution of 2.5° × 2.5° (latitude by longitude) with 17 vertical levels (Kalnay et al. 1996). Second, the SST dataset used in this study is derived from the National Oceanic and Atmospheric Administration Extended Reconstructed SST, version 3b (ERSST.v3b), dataset for the period 1950–2014, which has a horizontal resolution of 2° × 2° (Smith et al. 2008). Third, we also used the PDO index, which is defined as the leading principal component of monthly SSTAs over the North Pacific poleward of 20°N. More details on this index can be found in Mantua et al. (1997).

b. Methods

In this study, the quasigeostrophic refractive index (RI) is employed to understand the planetary wave propagation, which is defined by Chen and Robinson (1992) as
RI = \frac{\bar{q}_\varphi}{\bar{n} - c} - \left( \frac{k}{a \cos \varphi} \right)^2 - \left( \frac{f}{2NH} \right)^2, \quad (1)

where the meridional gradient of the zonal-mean potential vorticity \( \bar{q}_\varphi \) is given by the following:

\[
\bar{q}_\varphi = \frac{2\Omega}{a} \cos \varphi - \frac{1}{a^2} \left[ \bar{u} \frac{\cos \varphi}{\cos \varphi} \right] - \frac{f^2}{\rho_0} \left( \frac{\bar{r}}{N^2} \right)_z. \quad (2)
\]

Here, \( q \) is the potential vorticity, \( u_z \) is the vertical shear of zonal wind, \( \bar{u} \) is the zonal-mean zonal wind, \( c \) is the phase speed, \( k \) is the zonal wavenumber, \( N \) is the buoyancy frequency, \( H \) is the scale height (7 km), \( f \) is the Coriolis parameter, \( a \) is Earth’s radius, \( \Omega \) is Earth’s angular frequency, \( \rho_0 = \rho_s \exp(-z/H) \) is the background density of the atmosphere, \( \rho_s \) is the standard density of the atmosphere, \( z \) is the height, and \( \varphi \) is the latitude. If the phase speed \( c \) equals zero, the refractive index is treated as the stationary wave RI.

We use the two-tailed Student’s t test with an effective number of degrees of freedom \( N_{\text{eff}} \) to test the statistical significance of the linear regression coefficient and correlation coefficient between two autocorrelated time series (Pyper and Peterman 1998). The \( N_{\text{eff}} \) is approximately given as follows:

\[
\frac{1}{N_{\text{eff}}} \approx \frac{1}{N} + \frac{2}{N} \sum_{j=1}^{N} \left( 1 - \frac{j}{N} \right) \rho_{XX}(j) \rho_{YY}(j), \quad (3)
\]

where \( N \) is the sample size and \( \rho_{XX}(j) \) and \( \rho_{YY}(j) \) are the autocorrelations of the two sampled time series \( X \) and \( Y \) at time lag \( j \), respectively.

c. Model and numerical experiments

To support the analysis of the reanalysis datasets and explore the relationship between the SAV and PDO, two time-slice experiments were conducted using the Community Atmosphere Model, version 5 (CAM5), which is the atmospheric component of the Community Earth System Model (CESM). The CAM performs well in simulating various stratospheric processes (e.g., SPARC CCMVal 2010; Hu et al. 2016). CAM5 includes 30 vertical levels from the surface to 2.25 hPa, and the simulations adopt a horizontal resolution of 1.9° × 2.5° (latitude by longitude). More details about CAM5 can be found in Neale et al. (2012).

Two 50-yr experiments, which include a reference run (REF) and a sensitivity run (PPDO), are designed and conducted using CAM5. To investigate the responses of the SAV to the North Pacific SSTs directly, the numerical simulations in this study adopted an atmosphere-only mode, which is integrated in an atmospheric stand-alone configuration with prescribed SSTs and sea ice. In REF, the monthly mean year-2000 climatologies of surface emissions (including greenhouse gases and ozone-depletion substances) were obtained from the SRES A1B emission scenario developed by the Intergovernmental Panel on Climate Change. The SSTs used in REF are the observed monthly mean climatological SSTs from the Met Office Hadley Centre, which are based on the period 1950–2010, as shown in Fig. 1a. Configurations in PPDO are the same as those in REF except for the SST field. The SST field used in PPDO is the climatological SST in REF plus the negative SSTAs over the central North Pacific (35°–45°N, 150°E–150°W) between the positive PDO phases (normalized PDO index greater than 0.5 std dev) and the negative PDO phases (normalized PDO index lower than −0.5 std dev).
SSTCNP represent a portion of the PDO variability, high correlation coefficients are observed between the normalized SSTCNP and PDO indices based on both unfiltered \((r = 0.85)\) and 11-yr running-average \((r = 0.95)\) datasets during 1950–2014, which is shown in Fig. 2b. This indicates that the variance contributions from SSTCNP to the PDO based on the unfiltered data and 11-yr running-average data are approximately 72% and 90%, respectively. To avoid signals due to sea ice changes, the two experiments use the same sea ice fields.

3. Decadal relationship between the PDO and SAV

As the SAV is the strongest in boreal winter [December–February (DJF)], the following analysis focuses on this season. The variability of the polar vortex can be well represented by the polar cap height (PCH) anomaly (Baldwin and Thompson 2009). Here, we defined a PCH index, which is the normalized anomaly of the geopotential height averaged over 75°–90°N, 150°E–150°W with its linear trend being removed during the period 1950–2014 in DJF. A positive (negative) PCH index corresponds to a weakened (strengthened) SAV. Figure 2a shows the time series of the PCH indices after removing their linear trend from 1950 to 2014, both with and without ENSO signals removed using the linear regression method, and together with the time series of the 11-yr running average. In the following study, the unfiltered data and filtered data represent the original data and their 11-yr running average, respectively. The PCH index exhibits obvious decadal variations, accompanied with the pronounced “phase shifts” of the PDO at 20–30-yr intervals, that is, a weakened SAV during the 1950s–60s, a strengthened SAV during the 1970s–90s, and a weakened SAV since the 2000s. The time series of the PCH index with ENSO signals removed using the linear regression method are similar to those without ENSO signals removed. To remove ENSO signals clearly, they are removed prior to calculating the 11-yr running average. As seen in Fig. 2, the correlation coefficient between the PDO and PCH indices based on the unfiltered datasets is 0.28, which is statistically significant at the 95% confidence level according to the Student’s \(t\) test, and implies that the positive PDO phase corresponds to a weaker SAV. This is consistent with previous studies (Hurwitz et al. 2012; Woo et al. 2015; Kren et al. 2016). However, the fluctuations in the normalized PDO index appear to be out of phase with those in the PCH index on decadal time scales, whether or not the ENSO signals have been removed. The correlation coefficient between the PDO index with ENSO signals previously removed and the PCH index on 11-yr running average is \(-0.71\), which is statistically significant at the 95% confidence level via the two-tailed Student’s \(t\) test using \(N^{\text{eff}}\) (Pyper and Peterman 1998). Moreover, other choices of running means also have significant simultaneous correlations, and the correlation coefficient increases when the window size becomes larger; for example, the correlation coefficients between the PDO index with the ENSO signals removed and PCH index based on the 10-, 13-, and 15-yr running averages are \(-0.69\), \(-0.78\), and \(-0.86\), respectively. These results indicate that a strengthened (weakened) SAV on decadal time scales is closely related to the decadal variation of the PDO.

To identify the linkage between the PDO and the SAV on decadal time scales, Fig. 3a shows the correlation map between the filtered PCH index and the filtered SSTAs over the North Pacific. It is apparent that the PCH index has a significant positive correlation with the SSTAs in the central North Pacific and a negative correlation with the SSTAs in the Sea of Okhotsk, in the Gulf of Alaska, off California, and toward the tropics. Consistent with the correlation map, the SSTAs that are regressed on the PCH index resemble a horseshoe pattern, with statistically significant positive values in the central North Pacific surrounded by significant negative SSTAs in the Gulf of Alaska, off California, and toward the tropics (Fig. 3b). In addition, according to Bond et al.
we performed the empirical orthogonal function (EOF) reanalysis of the monthly SSTA field over the North Pacific (20.5°–65.5°N, 100°E–100.5°W), which is derived from the ERSST.v3b for the period 1950–2014, and is shown in Fig. 3c. The pattern shown in (c) denotes the positive PDO phase.

To verify the relationship between the PDO and SAV, Fig. 4a shows the regression of the detrended geopotential height and winds averaged over 10–50 hPa onto the PDO index during 1950–2014 in DJF. There are positive PCH anomalies accompanied with an anomalous anticyclonic flow over the Arctic. This indicates that there is a weaker SAV during the PDO positive phases, which is consistent with previous studies (Hurwitz et al. 2012; Woo et al. 2015; Kren et al. 2016). However, the regressed detrended and filtered geopotential height and winds onto the filtered PDO index show a negative geopotential height anomaly and a cyclonic flow over the Arctic stratosphere (Fig. 4b), which indicates that the positive PDO phase tends to result in a stronger SAV. Moreover, after removing ENSO signals from the geopotential height and winds, the in-phase relationship between the SAV and PDO still exists (Fig. 4c). This implies that on decadal time scales, the SSTAs over the North Pacific associated with the positive (negative) PDO index are closely linked to the strengthening (weakening) of the SAV. Note that the spatial pattern and magnitude of the regressed geopotential height and winds over the Arctic stratosphere with both ENSO and solar cycle signals removed (figure not shown) are highly similar to those that just had the ENSO signals removed (Fig. 4c). This suggests that the solar cycle may have no significant effects on the in-phase decadal relationship between the PDO and SAV.

Moreover, we performed two experiments using the state-of-the-art climate model, CAM5. Two 50-yr experiments, REF and PPDO, which only differ in the SST field over the North Pacific region (35°–45°N, 150°E–150°W; Fig. 1), were designed (see section 2c for more details). The differences in the geopotential height and horizontal winds over the Arctic stratosphere between PPDO and REF are presented in Fig. 4d. As expected, the negative geopotential height and cyclonic flow anomalies in the Arctic stratosphere can generally be reproduced in the simulations. This further confirms that the SSTAs over the North Pacific during the positive phases of the PDO on decadal time scales tend to strengthen the SAV.

4. Possible mechanisms of the PDO influence on the SAV

a. Tropospheric atmospheric teleconnections

A question arises as to how the SSTAs over the North Pacific associated with the PDO influence the SAV. The regression map of the detrended geopotential height anomalies at 200 hPa upon the normalized PDO index, which is based on the unfiltered and filtered data, is
There is clearly a wave train at the midlatitude, which extends from the North Pacific into the Eurasian continent. Additionally, the regressed map of the geopotential height shown in Figs. 5a,b exhibits a western Pacific (WP) teleconnection pattern over the North Pacific and a Pacific–North American (PNA) teleconnection pattern at the midlatitude (Horel and Wallace 1981; Wallace and Gutzler 1981). Consistent with the regressed geopotential height, the regression map of the streamfunction and winds at 200 hPa upon the normalized PDO index (Figs. 5d,e) exhibits statistically significant alternating positive and negative anomalies, along with alternating anticyclonic and cyclonic anomalies in the 200-hPa horizontal winds (Figs. 5d,e). The regressed tropospheric circulation anomalies at 850 and 500 hPa (figure not shown) are in good agreement with that at 200 hPa (Figs. 5a,b), which suggests that the wave train pattern is an equivalent barotropic structure.

The relationship between the PDO and the tropospheric teleconnection patterns according to Wallace and Gutzler (1981) are explicitly shown in Fig. 6. Strong correlations between the normalized WP and PDO indices at 200 hPa both exist based on the unfiltered data ($r = -0.32$, at the 95% confidence level) and on the filtered data ($r = -0.78$, at the 95% confidence level). The correlation coefficients between the normalized PNA pattern at 200 hPa and PDO indices based on the unfiltered and filtered data are 0.71 (at the 95% confidence level) and 0.82 (at the 95% confidence level), respectively. These indicate the close relationship between the PDO and wave trains in the troposphere. The
responses of tropospheric circulation to the SSTAs over the North Pacific associated with the positive PDO phases between PPDO and REF in CAM5 exhibit WP and PNA patterns in Figs. 5c and 5f, respectively. Hurwitz et al. (2012) noted that the positive SSTAs over the North Pacific tend to result in a strengthened WP teleconnection pattern. This suggests that a negative North Pacific SSTA may be consistent with a weakened WP teleconnection pattern. Kren et al. (2016) showed that the positive PDO phase is marked by the strengthened PNA pattern in the troposphere. Consistent with these two numerical model results, we further demonstrate that the positive PDO phases are consistent with a weakened WP pattern and a strengthened PNA pattern, which are both based on the unfiltered and filtered data in the NCEP1. The above results imply that the SSTAs over the North Pacific associated with the PDO have an important influence on the atmospheric teleconnection pattern changes in the troposphere, which is on both the unfiltered data and decadal time scales.

A negative WP and a positive PNA pattern are both characterized by a deep Aleutian low (Wallace and Gutzler 1981). Figures 7a–d show the regressions of the geopotential height and winds at 500 hPa during boreal winter from 1950 to 2014 with respect to the normalized PDO index. The regressed 500-hPa geopotential height over the North Pacific based on the unfiltered and filtered data both show statistically significant negative anomalies along with the cyclonic anomalies of horizontal winds over the North Pacific (Figs. 7a,c), which is consistent with the decreased sea level pressure there (not shown); this implies a strengthened Aleutian low. The strengthened Aleutian low in response to the decreased SSTAs over the North Pacific (Figs. 7e,f) can be simulated overall in CAM5 with a slight difference in the magnitude and position of the simulated Aleutian low. This is possibly related to the larger and slightly westward location of the jet stream in model simulations compared to the reanalysis data. This indicates that the positive phases of the PDO tend to result in a strengthened Aleutian low, which is consistent with previous studies (e.g., Latif and Barnett 1996; Hurwitz et al. 2012; Kren et al. 2016). As the stationary wave propagation is closely related to the tropospheric
subtropical jet (e.g., Hu et al. 2014), the strengthened tropospheric jet stream over the North Pacific (Figs. 7b,d,f) in both the reanalysis data and the simulations correspond to the deepened Aleutian low (Figs. 7a,c,e) and weakened WP and strengthened PNA pattern (Figs. 5 and 6). These tropospheric anomalies may be in favor of more horizontal stationary waves, which are propagated eastward along the strengthened jet stream over the North Pacific in the troposphere (figure not shown).

b. Planetary wave flux in the stratosphere

Changes in the SAV are closely related to the planetary wave activity in the stratosphere. There are more (fewer) planetary waves propagating from the troposphere into the stratosphere when the SAV weakens (strengthens) (e.g., Andrews et al. 1987; Jadin et al. 2010; Hu et al. 2014; Woo et al. 2015). As discussed above, the North Pacific SSTAs associated with the PDO can lead to significant WP and PNA teleconnection pattern anomalies. Some studies revealed that the atmospheric teleconnection patterns are closely related to the wave activity in the stratosphere (e.g., Orsolini et al. 2009; Hurwitz et al. 2012). It is necessary to next reexamine the relationship between the wave flux in the stratosphere and the PDO based on the unfiltered data and decadal time scales.

It is known that the WP and PNA patterns result from long Rossby waves (waves 1–3) (Hoskins and Karoly 1981; Chen 2002), and the tropospheric waves that can propagate into the stratosphere are the predominant wavenumber-1 and wavenumber-2 waves (Charney and Drazin 1961). As the eddy heat flux is proportional to the vertical flux of wave activity via the Eliassen–Palm flux (Edmon et al. 1980; Dunkerton et al. 1981), and to provide more information on wave activities, Figs. 8a–c show the regression of the eddy heat flux and its wavenumber-1 and wavenumber-2 components upon the PDO index during 1950–2014 for DJF, which is based on the unfiltered data. Consistent with previous studies (Hurwitz et al. 2012; Woo et al. 2015), the positive PDO phase tends to increase the eddy heat flux in the stratosphere with the predominant role of the planetary wavenumber-1 wave, which results in a further weakened SAV. It is interesting that on decadal time scales, the eddy heat flux decreases in the Arctic stratosphere under the condition of the positive PDO
phase shown in Figs. 8d–f, which is accompanied by a statistically significant decrease (increase) in the wavenumber-1 (wavenumber 2) component of the eddy heat flux at middle and high latitudes in the stratosphere. This implies that there are fewer planetary waves being propagated into the Arctic stratosphere during the positive PDO phase on decadal time scales, which are mainly contributed from the planetary wavenumber-1 wave. However, the planetary wavenumber-2 wave also plays an important role in the planetary wave propagation at the midlatitudes in the stratosphere. The simulated eddy heat flux in response to a cooler SST over the North Pacific significantly decreases in the middle and upper stratosphere at the midlatitudes (Fig. 8g), which is accompanied by a significant decrease in the wavenumber-1 component (Fig. 8h) and a slight decrease in the wavenumber-2 component (Fig. 8i). Although the responses of the wavenumber-2 component to the North Pacific SSTs in the simulations are different from that in the reanalysis, the decreased upward-propagated planetary waves in our simulations are mainly being contributed from the planetary wavenumber-1 component, which is consistent with that in the reanalysis. That is, the in-phase relationship between the PDO and SAV on decadal time scales is mainly related to the decreased planetary wavenumber-1 wave upward propagation into the stratosphere. The decreased SSTAs over the North Pacific associated with the positive phases of the PDO tend to inhibit the planetary wavenumber-1 wave propagated into the stratosphere, which further strengthens the SAV. The responses of the eddy heat flux in the troposphere on decadal time scales are similar to those on subdecadal time scales (figure not shown), which are consistent with the responses of tropospheric atmospheric teleconnections.

### c. Planetary wave propagation

The planetary wave flux in the stratosphere is related not only to the wave activity in the troposphere, but is also associated with the wave propagation conditions in
the upper troposphere and lower stratosphere (Hu et al. 2015). To understand the difference between the upward propagation of the planetary wavenumber-1 wave in response to the PDO based on the unfiltered time series and the filtered data, Fig. 9 also shows the regression of the RI for the zonal wavenumber-1 wave upon the normalized PDO index during 1950–2014 in DJF and the regression results based on the 11-yr running-average data. (g)–(i) As in (a)–(c), but for the differences in geopotential height and horizontal winds between PPDO and REF. The values in the stippled regions are significant at the 95% confidence level.

Fig. 8. Regression of the (a) eddy heat flux (K m s$^{-1}$), and its (b) wavenumber-1 and (c) wavenumber-2 components upon the normalized PDO index from NCEP1 during 1950–2014 for DJF. (d)–(f) As in (a)–(c), but for the regression results based on the 11-yr running-average data. (g)–(i) As in (a)–(c), but for the differences in geopotential height and horizontal winds between PPDO and REF. The values in the stippled regions are significant at the 95% confidence level.

It is apparent that the unfiltered RI under the positive PDO phase condition increases (decreases) in the high latitudes of the stratosphere (troposphere) (Fig. 9a). This implies that during the positive phase of the PDO, there are more planetary wavenumber-1 waves propagating into the high latitudes of the stratosphere, which is consistent with the increases in the eddy heat flux shown in Fig. 8b; this in turn results in a weakened SAV. However, the regressed RI on decadal time scales is different. From Fig. 9b, the regressed RI decreases at the middle and
high latitudes in the northern stratosphere, but increases in the northern troposphere, with the largest positive anomalies in the high latitudes of the upper troposphere. Therefore, the zonal wavenumber-1 wave is less likely to be propagated into the stratosphere when the PDO is in its positive phases on decadal time scales, which is consistent with the decreased upward wavenumber-1 wave flux in Fig. 8e. That is, the different responses of the planetary wave propagation to the PDO based on the unfiltered datasets or on decadal time scales are mainly related to the different responses of the RI, although the responses of their tropospheric circulation to the PDO are similar.

To determine what aspects of changes in the zonal-mean state contribute to the changes in the RI, Fig. 10 shows the regressed terms in the RI for zonal wave-number 1 on the PDO index based on the unfiltered and filtered data. Simpson et al. (2009) noted that the changes in the RI at the middle and high latitudes are mainly explained by the change in the meridional gradient of the zonal-mean potential vorticity $q_u$. In theory, for a given wavenumber, the second term of the RI in Eq. (1) is fixed, and any change to the third term in Eq. (1) is insignificant compared to changes to the first term. It is apparent that the results of $q_u$ are similar to the regressed RI shown in Fig. 9, which further indicates that the changes in the RI are mainly due to the changes in the $q_u$.

As the first term in $q_u$ [Eq. (2)] based on different time series is the same, the changes of $q_u$ are mainly related to changes in the second term $-a^{-2}[(\pi \cos \phi)/(\pi \cos \phi)] = U_{yy}$ and the third term $-f^2/\rho_0(\rho_0 c^2/N^2)z = U_{zz}$ in Eq. (2). As the $U_{zz}$ term is related to the background temperature gradient, it is called the baroclinic term. To distinguish the relative importance of the $U_{yy}$ and baroclinic terms, we also show the results of the $U_{yy}$ and the baroclinic terms (Figs. 10b,c,e,f). It is obvious that the baroclinic term is similar to $q_u$, that is, they both increase (decrease) in the stratosphere (troposphere) at high latitudes based on the unfiltered data; however, they both decrease (increase) in the stratosphere (troposphere) at middle and high latitudes based on the 11-yr running-average data. The changes in the $U_{yy}$ term are very different from $q_u$, although the $U_{yy}$ term, which is based on the unfiltered data at the midlatitudes, is also opposite to that based on the 11-yr running-average data. This implies that changes in $q_u$ are mainly due to the baroclinic term.

To further investigate what leads to the baroclinic term changes, Fig. 11 shows the regression of the zonal winds, temperature, vertical shear of zonal winds, and buoyancy frequency on the normalized PDO index, which is based on the unfiltered and filtered data during 1950–2014 in DJF. We can see that there are negative zonal wind anomalies in the Arctic stratosphere during the positive PDO phases (Fig. 11a), which is accompanied by positive temperature anomalies there (Fig. 11b). However, on decadal time scales, the zonal wind anomalies in the Arctic stratosphere during the positive PDO phases are positive (Fig. 11e) and accompanied by negative temperature anomalies there (Fig. 11f). The different structures of zonal winds and temperatures associated with the PDO based on the unfiltered data and decadal time scales may possibly result in the different changes in the baroclinic term.

Previous studies showed that the increased SSTs can lead to more vertically propagating waves being refracted poleward via alteration of the meridional temperature gradient in the subtropical troposphere and the zonal winds in the upper troposphere (e.g., Olsen et al. 2007; Shu et al. 2011; Hu et al. 2014). The wave propagation from the troposphere to the stratosphere is
sensitive to the vertical shear of the zonal winds and the vertical gradient structure of the buoyancy frequency $N^2$ (Chen and Robinson 1992; Li et al. 2007; Hu et al. 2014, 2015). Here, the positive phase of the PDO can result in a smaller meridional temperature gradient between the northern midlatitudes and high latitudes on subdecadal time scales, which is implied from Fig. 11b. Following the thermal wind relationship, changes in the meridional temperature gradient are accompanied by a decreased vertical shear of zonal winds in the upper troposphere and lower stratosphere in the northern subpolar region (Fig. 11c), and an increased buoyancy frequency below 70 hPa in the high latitudes (Fig. 11d). Chen and Robinson (1992) showed that a smaller zonal wind shear and a smaller vertical gradient in the buoyancy frequency tend to enhance the wave propagation. Therefore, there are more planetary waves being propagated into the stratosphere during the positive PDO phase on subdecadal time scales, which is consistent with the results of the eddy heat flux (Fig. 8).

However, changes in the temperature and zonal winds around the tropopause at the middle and high latitudes during the positive PDO phases on decadal time scales (Figs. 11e–h) are opposite to those on subdecadal time scales (Figs. 11a–d), that is, on decadal time scales, the positive phase of the PDO can result in a larger meridional temperature gradient between the northern midlatitudes and high latitudes (Fig. 11f), an increased shear of zonal winds in the upper troposphere and lower stratosphere in the northern subpolar regions (Fig. 11g), and a decreased buoyancy frequency below 70 hPa in the high latitudes (Fig. 11h). These conditions are not in favor of planetary wave propagation; therefore, there are fewer planetary waves being propagated into the stratosphere (Fig. 8) on decadal time scales. This suggests that the decadal relationship between the SSTs over the North Pacific and the SAV is different from those on only subdecadal time scales, which is mainly related to the wave propagation characteristics of the lowermost stratosphere and not to wave generation in the troposphere.

5. Conclusions and discussion

We investigate the decadal variability of the SAV and its link to the decadal variation of the PDO by using a combination of observation-based data analysis and climate model simulations. The SAV exhibits decadal
variations, that is, a weakened SAV in the 1950s–60s, a strengthened SAV in the 1970s–90s, and a weakened SAV since the 2000s. Our results suggest that the decadal variations in the PDO have important influences on the decadal variability of the SAV. A significant in-phase relationship between the PDO and SAV on decadal time scales exists, that is, decreases (increases) of the North Pacific SSTAs associated with the positive (negative) PDO phases are closely related to negative (positive) PCH anomalies over the Arctic stratosphere, which suggests a strengthened (weakened) SAV. Our results also imply that the decadal relationship between the North Pacific SSTAs and SAV is different from their relationships on subdecadal time scales. Previous studies revealed that during ENSO winters, the polar vortex tends to be weaker and warmer (e.g., Sassi et al. 2004; Garfinkel and Hartmann 2008; Xie et al. 2012), and our results further suggest that the tropical SST variations such as ENSO and the SSTAs over the North Pacific may have a different impact on the SAV.

Observations and modeling results both suggest that the decadal variability of the SAV is strongly affected by the North Pacific SSTAs associated with the PDO via dynamic processes on decadal time scales. Negative North Pacific SSTAs associated with positive phases of the PDO would lead to a deepened Aleutian low and a strengthened jet stream over the Pacific in the troposphere, which corresponds to a weakened WP pattern and a strengthened PNA pattern. These responses in the tropospheric circulation to the PDO on decadal time scales are similar to those that are based on the unfiltered data, which is also consistent with previous studies (Hurwitz et al. 2012; Woo et al. 2015; Kren et al. 2016). The tropospheric circulation anomalies in association with the positive or negative PDO phase tend to affect the planetary wave flux in the stratosphere by constructively or destructively interfering with the climatological planetary waves. However, our results find that the strengthened SAV during the positive PDO phase is mainly caused by less planetary wavenumber-1 waves propagating into the polar stratosphere on decadal time scales.

The planetary wave flux in the stratosphere is related not only to the climatological planetary waves (Hurwitz et al. 2012; Woo et al. 2015) but is also sensitive to the wave propagation conditions around the tropopause at middle and high latitudes (e.g., Li et al. 2007; Shepherd and McLandress 2011; Hu et al. 2014, 2015). Our results further show that the weakened planetary wavenumber-1 waves penetrating into the stratosphere to the PDO on decadal time scales are mainly related to the changes in the RI (i.e., the decreased RI anomalies at the middle and high latitudes in the northern stratosphere and the increased RI anomalies at high latitudes in the upper troposphere). This may impede the planetary wavenumber-1 wave from upward propagation into the stratosphere from the upper troposphere and, in turn, strengthen the SAV. Further investigation shows that the changes in the RI are mainly due to the changes in the $\overline{Q_0}$ via alteration of the baroclinic terms. Changes of

![Fig. 11. Regression of the (a),(e) zonal winds (m s$^{-1}$); (b),(f) temperature (K); (c),(g) vertical shear of zonal winds (s$^{-1}$); and (d),(h) buoyancy frequency (s$^{-2}$) on the normalized PDO index based on the (a)–(d) unfiltered data and (e)–(h) 11-yr running-average data during 1950–2014 in DJF. The anomalies of geopotential height in the stippled areas are significant above the 95% confidence level.](image-url)
meridional temperature gradients, shear of zonal winds, and buoyancy frequency during the positive PDO phases tend to result in more (fewer) planetary waves propagated into the stratosphere on subdecadal (decadal) time scales, which further weakens (strengthens) the SAV. The decadal relationship between the SSTs over the North Pacific and the SAV is different from those on only subdecadal time scales, which is mainly related to wave propagation characteristics of the lowermost stratosphere and not to wave generation in the troposphere.

Overall, this study examines the decadal variability of the SAV and highlights the role played by the decadal variations in the North Pacific SST in the SAV. In particular, this study provides some observational evidence that the decadal variations in the North Pacific SST associated with the PDO also play an important role in modulating the decadal variability of the SAV, which is mainly through modification of the planetary wave propagation from the troposphere into the stratosphere and the troposphere wave activity. Our results may have implications for decadal prediction over the Arctic in the future. It should be pointed out that the model results presented in this study are obtained with prescribed SSTs and not coupled to the ocean. It would be interesting to examine the relationship between the PDO and SAV on decadal time scales using the ocean–atmosphere coupled simulations in the future.

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REFERENCES


——, Z. Guan, Y. Guo, and S. Dhomse, 2016: Longitudinal asymmetric trends of tropical cold-point tropopause temperature and their link to strengthened Walker


