Synoptic-scale potential vorticity intrusion over northeastern China during winter and its influence on surface air temperature

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ABSTRACT
A regional potential vorticity (PV) intrusion (PVI) index, defined as the sum of the numbers of grids containing PVI within a certain area for each day, is used to reflect the day-to-day PVI variability over northeastern China during winter from 1979 to 2016. The synoptic-scale PVI variations and resultant surface air temperature (SAT) anomalies are identified by comparing the high and low PVI index cases. In high (low) PVI cases, significantly strong positive (negative) PV anomalies are found in the stratospheric midlatitudes, which intrude downward mostly within 90°–110°E into the upper troposphere to reach around 300 hPa and extend eastward to the east of 120°E, forcing an anomalous cyclonic (anticyclonic) circulation in the middle and lower troposphere over East Asia, with the anomalous northerlies (southerlies) of the forced lower-tropospheric cyclone (anticyclone) leading to significant negative (positive) SAT anomalies of less (greater) than −0.9°C (0.9°C), especially over northeastern China. In the stratosphere, the positive (negative) midlatitude PV anomalies over northern China are actually associated with a weakening (strengthening) of the polar vortex over the Eurasian continent for the high (low) PVI cases, resulting mostly from positive (negative) barotropic vorticity anomalies associated with static stability due to the meridional shear of anomalous zonal winds on the southern side of the anomalous Eurasian anticyclone (cyclone).

1. Introduction
Strong coupling has been found to exist between the stratosphere and troposphere (Baldwin, Cheng, and Dunkerton 1994; Kushner and Polvani 2004; Song and Robinson 2004). Planetary waves can propagate upward from the troposphere to stratosphere, thus decelerating the stratospheric jet through Rossby wave breaking (Charney and Drazin 1961). Conversely, anomalous signals in the stratospheric circulation can also penetrate downward, affecting both the circulation and weather in the troposphere (Baldwin and Dunkerton 2001; Thompson, Baldwin, and Wallace 2002). For example, the downward intrusion of potential vorticity (PV) from the stratosphere into the troposphere, also called tropopause PV intrusion (PVI), leads to cold surface air temperature (SAT) anomalies (Jeong et al. 2006; Kim, Jeong, and Kim 2009). Although the frequency distribution of synoptic-scale PVI in wintertime over the Northern Hemisphere and its corresponding SAT anomalies have been reported (Cai 2003; Škerlak et al. 2015), the spatial and synoptic-scale variations of the regional PVI during winter over midlatitude areas such as East Asia and their relationship with stratospheric circulation anomalies at high latitudes are still unclear.

Previous studies have related interannual SAT variations over East Asia to circulation systems such as the Arctic Oscillation (Wang et al. 2005; Chen et al. 2013), East Asian winter monsoon (Guo 1994), Siberian high (Ding 1990), and East Asian jet stream (Mao, Gong, and Fang 2007). However, for the synoptic-scale variation of the wintertime SAT over East Asia, how it is influenced by the day-to-day PVI activities is much less clear, especially over northeastern China where large populations reside and the East Asian trough in the middle and...
upper troposphere as a major weather system dominates frequently (Wang et al. 2007; Leung and Zhou 2015). Therefore, the objective of this study is to reveal the synoptic-scale behavior of PVI and its impact on the local SAT over East Asia.

2. Data and methods

2.1. Data

Daily atmospheric circulation datasets including geopotential height, temperature, and wind fields, derived from the NCEP–DOE Reanalysis-2 (Kanamitsu et al. 2002), with a horizontal resolution of 2.5° × 2.5°, are used for the period 1979–2016. For the SAT, weather station–observed surface temperature data over China are used, which have been interpolated as a daily gridded dataset with a high resolution of 0.25° × 0.25° (Wu and Gao 2013). The winter season refers to the traditional wintertime months of December, January, and February, with 37 winters in the analysis period.

2.2. Methods

All the data are processed following the approach of Cai (2003). The data on 29 February in the 10 leap years from 1979 to 2016 are excluded. To obtain the climatological annual cycle, we first take the average of the daily data for each of the 365 days over the entire analysis period, and then calculate 31-day running means. Daily anomalies are obtained by subtracting the annual cycle from the raw data. Daily standard deviation maps can be derived from the anomaly maps. PVI events can be measured by a Boolean-type function proposed by Cai (2003):

\[
PVI_{300}(x, y, t) = \begin{cases} 
1, & \text{if } P_{2.5}(x, y, t) > P_{2.5 \text{ annual}}(x, y, \text{day}), \\
+0.5[SD_{P_{2.5}}(x, y, \text{day})] & \text{and } P_{2.5} > 300 \text{hPa}, \\
0, & \text{otherwise} 
\end{cases}
\]

where \((x, y)\) are longitude and latitude, \(t = (\text{year }- 1979) \times 365 + \text{day}, \text{year } = 1979, 1980, \ldots, 2016\) and \(\text{day } = 1, 2, \ldots, 365\); ‘\(\)’ denotes the zonal mean averaging operator. The dynamic tropopause refers to the PV surface with a value of 2.5 PVU (1 PVU = \(10^{-6}\) m² s⁻¹ K kg⁻¹). \(P_{2.5}\) represents the daily pressure maps on the PV 2.5 surface that are used to diagnose PVI along the dynamic tropopause, obtained by the methods of Morgan and Nielsengammon (1998). \(P_{2.5 \text{ annual}}\) is the annual cycle of \(P_{2.5}\), and \(SD_{P_{2.5}}\) is the annual cycle of the daily standard deviation of \(P_{2.5}\), derived from the anomaly maps. The regions with \(PVI_{300} = 1\) are places where PV surfaces descend and intrude into the troposphere.

The frequency of PVI at each grid point in winter is calculated by the expression

\[
\frac{1}{N} \sum_{t=1}^{N} PVI_{300}(x, y, t),
\]

where \(N = 37 \times 90\), is the total number of days in 37 winters. The regional PVI (RPVI) index for each day over a particular region can be defined as the sum of the numbers of grid points at which the PVI arises within a certain domain. Thus, the daily RPVI index is calculated as

\[
\text{RPVI}(t) = \sum_{y=x^1}^{y^2} \sum_{x=x^1}^{x^2} PVI_{300}(x, y, t),
\]

in which \((x^1-x^2)\) and \((y^1-y^2)\) are the latitudinal and longitudinal ranges of the region, respectively. Based on the standardized RPVI index time series, we can categorize the PVI behavior as normal-, high-, and low-index cases. Actually, the high-index (low-index) cases correspond to those days when the standardized RPVI index is above (below) 0.5 (note here that 0.5 is half the standard deviation), with the frequency of PVI at each grid point for high (low) RPVI index cases being calculated by the expression

\[
\frac{1}{n} \sum_{t=1}^{n} PVI_{300}(x, y, t),
\]

For high (low) RPVI index cases, \(t = 1, 2, \ldots, n\) are those days with high (low) RPVI index.

Following Hoskins, McIntyre, and Robertson (1985), the isobaric coordinate version of PV is

\[
PV = -g \left( \frac{\partial \theta}{\partial p} \zeta_a - g \left( \frac{\partial v}{\partial y} \frac{\partial \theta}{\partial p} - \frac{\partial u}{\partial x} \frac{\partial \theta}{\partial p} \right) \right),
\]

where \(\zeta_a = \frac{\partial \zeta}{\partial x} - \frac{\partial \zeta}{\partial y}\) represents absolute vorticity, \(u\) is zonal wind, \(v\) is meridional wind, \(f\) is the Coriolis parameter, \(\theta\) is potential temperature, and \(g\) is gravitational force. Here, we diagnose quantitatively the relative contributions to the PV anomaly from the barotropic term \((\frac{\partial \theta}{\partial p} \zeta_a)'\) and the baroclinic term \(-g (\frac{\partial v}{\partial x} \frac{\partial \theta}{\partial p} - \frac{\partial u}{\partial y} \frac{\partial \theta}{\partial p})'\). In turn, \((\frac{\partial \theta}{\partial p} \zeta_a)'\) can be further separated into the mean static stability–related shear anomalies of the zonal wind \((\frac{\partial g}{\partial p})(\frac{\partial \theta}{\partial y})'\) and the meridional wind \((\frac{\partial g}{\partial x})(\frac{\partial \theta}{\partial x})'\) along with the mean absolute vorticity–related static stability anomaly \((\frac{\partial \theta}{\partial p})'\). Note that an overbar represents a time-mean operator to calculate the climatological annual cycle, and a prime denotes the daily anomaly from the climatological value.
3. Synoptic-scale-PVI-forced tropospheric circulation and SAT anomalies

3.1. Frequency of synoptic-scale PVI in winter over northeastern China

As suggested by Cai (2003), the place where the pressure at the 2.5-PVU PV surface is greater than 300 hPa ($PVI_{300} = 1$) can represent high stratospheric PV penetrating the troposphere. As an example, Figure 1(a) illustrates an event of high PV intruding into the troposphere over East Asia. The 2.5-PVU PV surface (tropopause), like a funnel, descends sharply downward to about 400 hPa over northeastern China. The frequency of PVI at each grid point in all 37 winters calculated by Equation (2) is presented in Figure 1(b), as well as the synoptic-scale variance of PVI. Note that the North Pacific, where transient eddies occur frequently (Blackmon et al. 1977), is also a region of PVI occurrence with high frequency, consistent with the results of Cai (2003). Actually, this high-frequency PVI center accords well with that of the PVI variance (Figure 1(b)). Interestingly, larger differences in PVI occurrence arise over northeastern China and its surrounding areas, with the frequency ranging from about 5% to 30%, corresponding well to the larger variance (Figure 1(b)), indicating that the PVI variations over this region are more intense on the synoptic time scale. As such, the domain around northeastern China ($30^\circ$–$55^\circ$N, $105^\circ$–$135^\circ$E) is defined as the key region to reflect the PVI activities. The RPVI index over the key region for each day, calculated by Equation (3), is thus used to represent the regional PVI status and anomaly over northeastern China. Statistically, it is found that within all 37 winters there are 965 (1171) days with high (low) RPVI index. That is, the occurrence frequency of high (low) RPVI index cases is 29% (35%) relative to the total number of wintertime days. Figure 1(c,d) show the frequency of PVI at each grid point for high and low RPVI index cases, respectively, calculated using Equation (4). It is clear that a frequency of PVI of more than 50% exists over northeastern China in high RPVI index cases (Figure 1(c)), whereas the frequency of PV intruding into the troposphere over northeastern China in low RPVI index cases is less than 10% (Figure 1(d)). This raises questions as to what the reason might be for this occurrence of high and low frequency of PVI over northeastern China, what the difference is in the induced circulation anomalies between high and low frequencies of PVI, and how the induced circulation anomalies influence SAT over northeastern China.

3.2. Induced circulation anomalies associated with high and low RPVI index

To address the above issues, Figure 2 shows the composite vertical structure of PV anomalies averaged over $30^\circ$–$55^\circ$N and the corresponding atmospheric

![Figure 1](image-url)
adjustments in high and low RPVI index cases. In high RPVI index cases (Figure 2(a)), significantly strong positive PV anomalies from 10 to 50 hPa within 90°–110°E intrude downward to 300 hPa, where the tropopause (2.5-PVU PV) is located, and extend eastward to the east of 120°E, exhibiting an equivalent barotropic structure. Associated with such positive PV anomalies above 300 hPa and around 120°E are positive (negative) potential temperature anomalies above (below) 300 hPa, which result from the adjustment of atmospheric static stability, as suggested by Hoskins, McIntyre, and Robertson (1985). Corresponding to the positive PV anomalies above 300 hPa, strong negative geopotential height anomalies are induced in the middle and lower troposphere, with the anomaly center located at around 300 hPa and 120°E (Figure 2(c)). Such negative geopotential height anomalies tend to extend eastward and stretch to the surface within 120°–150°E (as discussed later). As a consequence of geostrophic balance, anomalous northerlies (southerlies) are inevitably

Figure 2. (a, b) Longitude–vertical cross section of composite PV anomalies (shading; units: PVU) and potential temperature anomalies (contours; units: K) averaged over 30°–55°N in (a) high RPVI index cases and (b) low RPVI index cases. (c, d) Geopotential height anomalies (shading; units: m) and meridional wind anomalies (contours; units: m s⁻¹) averaged over 30°–55°N in (c) high RPVI index cases and (d) low RPVI index cases. The red dashed contours in (a, b) represent climatological PV values averaged over 30°–55°N in winter, and PV2.5 is highlighted by the thickened contour. Stippling denotes PV anomalies that are statistically significant at the 99% confidence level. Contours are only shown when the potential temperature anomalies are significant at the 99% confidence level.
induced to the west (east) of the central region, around 120°E, of the negative geopotential height anomalies, with the anomalous northerlies advecting more cold air from high latitudes into midlatitudes over East Asia. The opposite situation is apparent for the low RPVI index cases (Figure 2(b,d)), with strong negative PV anomaly signals intruding from the stratosphere into the troposphere (Figure 2(b)) to force strong positive geopotential height anomalies in the troposphere, thus favoring SAT warming due to anomalous southerlies west of 120°E (Figure 2(d)).

3.3. Impact of the RPVI-induced circulation anomalies on SAT over China

To further clarify how the stratospheric PV anomalies affect the SAT over northeastern China through the induced circulation anomalies, composite maps of the PV anomalies at 30 hPa and the geopotential height anomalies at 1000 hPa are displayed in Figure 3. For the high RPVI index cases, strong negative PV anomalies at 30 hPa are observed over Siberia, accompanied by an anomalous anticyclone (Figure 3(a)). To the south are positive PV anomalies over northern China (Figure 3(a)), which in turn force anomalous northerlies to arise in the lower troposphere to affect northeastern China (Figure 3(e)). As mentioned earlier, the anomalous anticyclone (Figure 3(a)) is associated with a weakened polar vortex over continental Eurasia, which also leads to the occurrence of an anomalous anticyclone over Siberia at 1000 hPa (Figure 3(e)). Note from Figure 3(c) that, in the stratosphere, significant PV anomalies generated by anomalous barotropic vorticity associated with static stability exhibit a similar distribution to the total PV anomalies as in Figure 3(a), in which the largest contribution to the positive PV anomalies over northern China is from the static stability- related meridional shear of the anomalous zonal winds on the southern side of the anomalous Eurasian anticyclone for the high RPVI cases, while other terms including the static stability-related zonal shear of anomalous meridional wind, absolute vorticity-related static stability anomaly, and baroclinic vorticity anomaly make minor contributions to the total PV anomalies (not shown). As shown in Figure 2(a), due to such positive PV anomalies penetrating downward into the upper troposphere over 30°–55° N, positive geopotential height anomalies are induced near the surface west of 120°E, with negative geopotential height anomalies to the east, corresponding well to a huge anomalous anticyclone over Siberia and an anomalous cyclone over and around Japan at 1000 hPa (Figure 3(e)). Consequently, the strong northerlies between the anomalous cyclone and anomalous anticyclone lead to significant negative SAT anomalies of less than −0.9°C not only over northeastern China, but also over northwestern China (Figure 4(a)).

The opposite situation is found for the low RPVI index cases (Figure 3(b, d and f)). An anomalous cyclone is present in the stratosphere over the Eurasian continent (Figure 3(b)), indicating the polar vortex center is mostly located over the Eastern Hemisphere. The meridional shear of anomalous zonal winds on the southern side of the anomalous cyclone (Figure 3(b)) generates significant negative PV anomalies over northern China (Figure 3(d)), with the latter propagating downward into the upper troposphere to induce cyclonic and anticyclonic anomalies in the lower troposphere (Figure 3(f)). Thus, the near-surface anomalous southerlies on the western side of the anticyclone over and around Japan (Figure 3(h)) lead to positive SAT anomalies of greater than 0.9°C over northeastern China (Figure 4(b)).

4. Summary and discussion

This study examines the regional PVI variations on the synoptic time scale in wintertime. A daily RPVI index is defined as the sum of the number of grids containing PVI within a certain area to reflect the day-to-day regional PVI behavior over northeastern China. The results show that there is a frequency of about 30% for high RPVI index cases in all winter seasons, which is slightly less than for low RPVI index cases. Over northeastern China, however, there is a frequency exceeding 50% for PVI in high RPVI index cases, while it is less than 10% for low RPVI index cases. In high RPVI index cases, significant negative PV anomalies are found to exist in the stratosphere over continental Eurasia, which are associated with a weakened polar vortex. To the south are positive PV anomalies over northern China, which result largely from positive barotropic vorticity anomalies associated with static stability due to the meridional shear of anomalous zonal winds on the southern side of the anomalous Eurasian anticyclone. Such positive stratospheric PV anomalies can intrude downward into the upper troposphere over 30°–55°N, with an anomalous Siberian anticyclone and East Asian cyclone induced in the lower troposphere. Consequently, the near-surface strong northerly winds between the anomalous anticyclone and cyclone lead to negative SAT anomalies of less than −0.9°C over northeastern China. In low RPVI index cases, meanwhile, the polar vortex leans toward the Eurasian continent in association with an anomalous cyclone in the stratosphere, accompanied by significant positive PV anomalies. The stratospheric negative PV anomalies over northern China also
penetrate downward to induce an anomalous anticyclone in the lower troposphere over and around Japan, with corresponding anomalous southerly winds resulting in positive SAT anomalies exceeding 0.9°C over northeastern China.

It should be acknowledged that the present study mainly emphasizes the impact of the surface-level anomalous circulation over and around Japan induced by PVI on SAT anomalies, but the contribution of the adjacent anomalous cyclone or anticyclone over Siberia to SAT anomalies is not discussed. Besides, the synoptic-scale variation of PVI does not consider different interannual variation backgrounds. The relationship between the interannual variation of the polar vortex and PVI over northeastern China is worth studying. These questions will be addressed in future research.

**Figure 3.** (a, b) Composite field of PV anomalies (shading; units: PVU) and wind anomalies (vectors; units: m s$^{-1}$) at 30 hPa in (a) high RPVI index cases and (b) low RPVI index cases. (c, d) Static stability-related barotropic vorticity anomalies ($-g \frac{\partial}{\partial p} \zeta_a$) (shading; units: PVU) at 30 hPa in (c) high RPVI index cases and (d) low RPVI index cases. (e, f) Geopotential height anomalies at 1000 hPa (shading; units: m) and wind anomalies (vectors, m s$^{-1}$) in (e) high RPVI index cases and (f) low RPVI index cases. Stippling denotes anomalies that are statistically significant at the 99% confidence level. Vectors are only shown when both zonal and meridional wind anomalies are significant at the 99% confidence level.
Figure 4. SAT anomalies in (a) high RPVI index cases (shading; units: °C) and (b) low RPVI index cases. Stippling denotes anomalies that are statistically significant at the 99% confidence level.

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