Case Study of Potential Vorticity Tower in Three Explosive Cyclones over Eastern Asia

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ABSTRACT

Three cases of explosively developing extratropical cyclones over eastern Asia are analyzed using ERA-Interim data. The morphological characteristics of the upper-tropospheric potential vorticity (PV) were examined. The common feature of all of these three cases is a hook-shaped high-PV streamer wrapping counterclockwise around the center of surface cyclones on the southern and eastern sides and an arch-shaped low-PV tongue that wrapped the high-PV hook head from the north. The hook-shaped high-PV tongue overlaps with the maximum centers of both the relative vorticity and static stability parameter, indicating the stratospheric nature of the PV source inside the hook-shaped high-PV tongue.

The analysis indicates that there existed a deep tower of high PV above the surface cyclone at the time when these cyclones underwent explosive cyclogenesis. The high PV in the upper troposphere originates from the polar stratospheric PV reservoir associated with the tropopause-folding process. The high PV in the lower troposphere, however, is associated with the latent heat release, as nearly 70%–90% of the high-PV values in the lower troposphere reside in the region where the rainfall is the heaviest.

1. Introduction

Ever since Hoskins et al. (1985) published their seminal paper on PV theory in order to understand the dynamics of cyclones, PV, as a key variable reflecting both the dynamic and thermodynamic processes, has been widely used to analyze the evolution of cyclones and to diagnose convective weather systems (e.g., Liang et al. 2010; Campa and Wernli 2012). Thus, PV perspective was regarded as “a major weapon in the armory of atmospheric scientists when viewing data from the real atmosphere or from computer models simulating it” (Hoskins 2015, p. 2). Many researchers (e.g., Thorncroft et al. 1993; Martin 1998; Posselt and Martin 2004) indicated that the upper-tropospheric high PV might extend equatorward from the poleward PV reservoir and curve cyclonically to a “hook” shape (known as a PV hook) during intense deepening processes of extratropical cyclones. When an extratropical cyclone developed from deepening phase to mature phase, PV would typically evolve from the hook-shaped distribution into a treble clef shape. Novak et al. (2010) investigated 36 intense precipitation banded events that occurred during cold seasons from 2002 to 2008 in North America and revealed that the majority of intense precipitation bands developed along the northern portion of the hook-shaped upper-tropospheric PV.

A number of case studies (e.g., Davis and Emanuel 1988; Kuo et al. 1991; Campa and Wernli 2012) showed that the upper-tropospheric PV was associated with the development of low-level cyclogenesis, and there were three distinct positive PV anomalies in an extratropical cyclone: surface, lower-tropospheric, and upper-tropospheric PV anomalies. During the mature phase of the cyclone development, these three positive PV anomalies often became vertically aligned and formed a so-called PV tower, representing a tropospheric spanning column of air with anomalous high-PV values. These three PV anomalies could induce a...
strong cyclonic circulation extending from the tropopause to surface, exerting a significant impact on the development of extratropical cyclones. Wang and Rogers (2001) presented a series of composite vertical structures of PV and wind speed for explosively deepening cyclones over the North Atlantic and showed that upper- and lower-level PV anomalies could create a coherent cyclonic circulation around the tropopause center from the tropopause to surface when both anomalies were developed. They suggested that such a coherent structure can promote deepening of cyclones. Wernli et al. (2002) analyzed the dynamical aspect of the winter storm Lothar and suggested that the formation of positive upper- and lower-level PV anomalies can induce low-level cyclonic circulation, and the vertical coupling of PV anomalies is the key process for the dynamical cause of the rapid-intensification phase. Lim and Simmonds (2002) indicated that the vertically well-organized structure (especially in explosive cyclones) would most likely develop into a larger and stronger cyclone and might last longer than the shallow systems.

In a numerical study, Martin (1998) noticed that there was dynamic coupling between the upper-tropospheric PV morphology associated with a cyclone and the thermal structure of the underlying troposphere. Given the fact that a high (low) upper-tropospheric PV is characterized by a cold (warm) column of air beneath it, Martin (1998, p. 303) reasoned that “the presence of an upper-tropospheric treble clef PV signature serves as a sufficient condition for asserting the presence of a warm occluded thermal structure in the underlying troposphere.”

Although the upper-tropospheric morphology and the vertical distribution of PV have been investigated by a number of researchers, the relationship between the morphological characteristics and PV tower during explosive deepening of extratropical cyclones has not been discussed extensively. And the influence of latent heat release on the low-level positive large value of the PV tower needs to be analyzed further. In this paper, three extratropical explosive cyclones over eastern Asia will be investigated. The development of these cyclones will be examined through their horizontal distributions of upper-tropospheric PV and the PV tower, as well as the connection between the upper-tropospheric PV characteristics and explosive deepening. We will pay much attention to the evolution of upper-tropospheric PV morphological characteristics and focus on the relationship between the development of PV vertical characteristics and explosive deepening in an effort to understand the possible mechanisms of the explosive development of extratropical cyclones.

The rest of the paper is organized as follows. Section 2 describes the data sources. Section 3 introduces three selected cases of explosively developing cyclones. Section 4 analyzes the characteristics of upper-tropospheric PV distributions of these selected cyclone cases. The structure of the PV tower is analyzed in section 5. Section 6 discusses the sources of the PV tower in the middle to upper troposphere, the lower troposphere, and near the surface. Finally, conclusions are given in section 7.

2. Data

The data used in the present study are from the ERA-Interim (Dee et al. 2011). ERA-Interim is a global atmospheric reanalysis of the recorded climate observations. It covers the global region and is available at 0000, 0600, 1200, and 1800 UTC every day, with a horizontal resolution of $0.75^\circ \times 0.75^\circ$. It includes geopotential height, potential vorticity, air temperature, $U$ component of wind, $V$ component of wind, vertical velocity, and relative vorticity at 37 vertical pressure levels.

3. Case selection

The northwestern Pacific is one of the regions with the most frequent occurrence of explosive cyclones in the world (Sanders and Gyakum 1980; Yoshida and Asuma 2004; Allen et al. 2010; Black and Pezza 2013). In the present study, three cases of explosive cyclones that occurred over this region are selected (Fig. 1). Cyclone A occurred from 26 March to 2 April 2004. This cyclone underwent explosively deepening processes twice. Its first explosive deepening (stage I, from 1200 UTC 26 March to 1200 UTC 30 March 2004) occurred over land, and its second explosive deepening (stage II, after 1200 UTC 30 March 2004) occurred over the Okhotsk Sea. Cyclone B had the strongest deepening rate among all three cases. It occurred from 12 to 18 January 2013. It was generated over the eastern coast of the Philippine Islands, and its rapid deepening occurred in the extratropical zone, so it was regarded as an extratropical explosive cyclone (Hirata et al. 2015). Cyclone C was a storm that caused two shipwrecks, from which 26 people died or went missing. This cyclone occurred from 24 to 26 November 2013.

In addition, the following aspects were considered in the selection of these three cases. First, their tracks, including the northern, southern, and central routes, were representative of extratropical cyclone tracks over eastern Asia (see Fig. 1). Second, their genesis locations and regions of explosive deepening were different. The generation of cyclone A was over the
land, and its explosive deepening was over the ocean. For cyclone B, both the generation and the explosive deepening were over the ocean. The generation and the explosive deepening of cyclone C were both over the coastal region. Third, according to Sanders (1986), all three cyclones can be classified as strong explosive cyclones, because the maximum deepening rates were 1.8 bergerons (1 bergeron = 1 hPa h⁻¹) for cyclone A (Fig. 2a), 3.9 bergerons for cyclone B (Fig. 2b), and 2.0 bergerons for cyclone C (Fig. 2c), using the deepening rate for 12 h.

4. Morphological characteristics of the upper-tropospheric PV

Figure 3 shows the maps of the 300-hPa PV (contours) and relative vorticity (shading) at the time when the cyclones underwent explosive deepening. The common feature in each panel of Fig. 3 is that the high-PV center above the surface cyclone was connected to the PV reservoir in the polar region via a hook-shaped high-PV tongue that extended southward from high latitudes on the western side, with its hook wrapping counterclockwise around the center of the surface cyclone. This phenomenon is described as a PV streamer (Martius et al. 2008). Meanwhile, on the eastern side of the surface cyclone, the polar high-PV reservoir was pushed northward by an arch-shaped low-PV tongue (<1 PV unit; 1 PVU = 10⁻⁶ K kg⁻¹ m² s⁻¹) that wrapped around the high-PV hook head from the north. After the explosively deepening period, the arch-shaped low-PV tongue continuously expanded westward on the northern side and gradually cut off the high-PV hook head from the polar high-PV reservoir. As a result, the hook-shaped structure lost its original shape and was eventually disassembled. Therefore, these three cyclones had a very similar evolution of the upper-tropospheric PV morphology during their explosively deepening developments.

We have analyzed the morphology of PV at other levels and found that such a pair of the hook-shaped high-PV tongue expanding southeastward on the western side and the arch-shaped low-PV tongue expanding northwestward on the eastern side only existed in the layers between 500 and 200 hPa. Since the high-PV reservoir resides in the polar stratosphere, the presence of the hook-shaped high-PV tongue in the midlatitude upper troposphere, or the high-PV streamer, is the manifestation of tropopause-folding processes above the surface cyclones.

To illustrate the stratospheric nature of the hook-shaped high-PV tongue, we also plot the relative vorticity (shading in Fig. 3) and the vertical gradient of
potential temperature (shading in Fig. 4) fields at 300 hPa. The vertical gradient of potential temperature is calculated as the difference between the 250- and 350-hPa potential temperatures divided by 100, measuring the static stability of the layer. It is clearly seen that high PV values were collocated with larger values of relative vorticity and stronger stratification for all three cases. In particular, the maximum centers of both relative vorticity and vertical gradient of potential temperature were located in the high-PV hook region, which was more or less directly above the surface cyclone center. This illustrates that the presence of the hook-shaped high-PV tongue in the midlatitude upper troposphere was a result of stratospheric air intrusion processes above the surface cyclones.

5. Synopsis of PV tower formation

A deep high-PV tower is a typical feature of most extratropical mature cyclones (Campa and Wernli 2012). The high-PV intrusion into the middle to upper troposphere originates from the stratosphere associated with tropopause-folding processes. Meanwhile, high PV also is stretched upward from the lower levels. As a result, a deep tower of high PV (≥1 PVU) (i.e., a PV tower) extends vertically throughout the whole troposphere (Rossa et al. 2000; Wang and Rogers 2001).

To quantify the temporal evolution of the intensity of the PV tower as well as its vertical structure, we average gridded PV values in a 2°(latitude) × 2°(longitude) box following the surface cyclone under consideration. The box is centered at the surface cyclone. The area used for the average is similar to a circle with a radius of 200 km around the cyclone center (Campa and Wernli 2012). The moment when the area-averaged PV values are all greater than 1 PVU throughout the troposphere corresponds to the PV tower formation.

During stage I of cyclone A, a tongue of high PV dipped downward from the upper troposphere to the middle troposphere, with the 1-PVU contour extending downward to the lowest point of 450 hPa at 0000 UTC 27 March 2004 (Fig. 5a). Meanwhile, the
lower-level high PV bowed upward to the highest point of 650 hPa. There was no PV tower formation during stage I of cyclone A since the upper-level high PV and lower-level high PV were not connected with each other. During stage II of cyclone A, a PV tower formed at 0000 UTC 1 April 2004 (Fig. 5b), which corresponds to the time when the cyclone reached its deepest intensity (Fig. 2a). It is found that the increase of lower-level PV was about 12 h in advance of the PV tower formation. The formation process started at 0600 UTC 31 March 2004 when the lower-level positive PV began to increase. At 1800 UTC, the lower-level PV reached a maximum value of 2.6 PVU at 750–800 hPa.

For cyclone B, the duration of the PV tower was the longest among these three cases, lasting from 1200 UTC 14 January to 1200 UTC 16 January 2013 (Fig. 5c). At 1800 UTC 14 January, when the fastest deepening occurred (with a deepening rate of 3.9 bergerons), the PV tower reached its strongest state, with PV values larger than 2 PVU throughout the layer from 250 to 950 hPa. As during stage II of cyclone A, there was also a distinct maximum PV center greater than 2.5 PVU at lower levels (750 hPa) during the explosive development phase of cyclone B.

The PV tower in cyclone C formed at 1800 UTC 24 November 2013 (Fig. 5d). At this time, the upper-tropospheric PV values were larger than 4 PVU at 250 hPa, and the lower-level PV values were larger than 1.5 PVU. Unlike the case of cyclone B and stage II of cyclone A, there was no distinct maximum PV center in the lower troposphere, and the intrusion of the upper-level high PV into the middle troposphere also appears weak for cyclone C.

6. Sources of large PV in PV tower

As reported by Campa and Wernli (2012), a PV tower is made of three vertically aligned parts of large positive PV anomalies: one in the middle to upper troposphere, one in the lower troposphere, and one near the surface. The rapid development of extratropical cyclones is regarded as an interplay of three positive potential vorticity anomalies (Davis and Emanuel 1988; Kuo et al. 1991; Campa and Wernli 2012). Next, we discuss the sources of large PV in the middle to upper troposphere.
(500–200 hPa), in the lower troposphere (950–500 hPa), and near the surface (below 950 hPa).

a. Middle to upper troposphere

As is well documented in the literature, the dynamic tropopause folding or stratospheric intrusion is the source of large PV in the middle to upper troposphere (e.g., Reed and Danielsen 1958; Hoskins et al. 1985; Martin 1998). The west–east cross-sectional diagrams of PV and potential temperature (Fig. 6) indicate that the descending of large PV and warm potential temperature takes place on the eastern side of surface cyclones in all three cases. This is consistent with the results shown in Figs. 3 and 4: namely, that the descending of the tropopause was accompanied with a high-PV and high-potential-temperature hook that wraps around surface cyclones from the south and the east during the explosive development stage. On the western side of the descending tropopause was a tall column of cold air. This, together with the intrusion of warm and high-PV stratospheric air into the middle to upper troposphere, led an enhancement of the west–east thermal contrast, strengthened the southerly wind shear, and enhanced upper-level cyclonic circulation.

b. Lower troposphere

Large PV in the layers between 650 and 950 hPa corresponds to the lower-tropospheric part of a PV tower. Campa and Wernli (2012) attributed the large positive PV to a diabatic process. The classic PV dynamics predicts that diabatic heating in the middle atmosphere would result in a PV dipole with negative PV anomalies aloft and positive PV anomalies below (Hoskins and James 2014). There is ample evidence suggesting that

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**FIG. 5.** Temporal evolution of the vertical profile of the area-mean PV (PVU; see text for the definition of area mean). (a) Stage I of cyclone A, (b) stage II of cyclone A, (c) cyclone B, and (d) cyclone C.
latent heat release in the middle troposphere is responsible for large positive PV anomalies in the lower troposphere (e.g., Brennan and Lackmann 2005). The negative PV anomalies above the layer where latent heat release is a maximum also partially cancelled out part of the large PV anomalies that originated from the stratosphere, resulting from the tropopause-folding processes. This explains why there exists a large PV center separated from the upper-level high-PV reservoir during the explosive development phase of cyclones.

To verify this view and confirm the association of large PV values in the lower troposphere with the latent heating process, we have developed the PVPW index, which measures the ratio of the area of high PV ($\geq 1$ PVU) in the region of high values of vertically integrated precipitable water (proportional to latent heat) to the total area of high PV at each layer in the vicinity of a surface cyclone. Specifically, we chose a box of $15^\circ$ (latitude) $\times 15^\circ$ (longitude) centered at the moving cyclone. We calculate the PVPW index according to

$$\text{PVPW} = \frac{\text{Area}(\text{PV} \geq 1 \text{ and } \text{PW} > \text{PW}_0)}{\text{Area}(\text{PV} \geq 1)} \times 100\%,$$

where PW denotes the vertically integrated precipitable water and PW$_0$ corresponds to a threshold value of the vertically integrated precipitable water that has been taken as the area mean of the precipitable water over the box. Obviously, the numerical range of the PVPW is between 0% and 100%. The maximum possible value of PVPW corresponds to the situation in which the entire area of PV $\geq 1$ in the vicinity of a cyclone [covered by a box of $15^\circ$ (latitude) $\times 15^\circ$ (longitude) centered at the cyclone] has experienced a substantial amount of latent heat release (or has a large amount of rainfall).
Displayed in Fig. 7 are temporal evolutions of the vertical profiles of the $P_{VPW}$ index during the explosive intensification period of the three cyclones. In stage I of cyclone A, a maximum center of the $P_{VPW}$ index with a peak value exceeding 90% appeared from 1200 UTC 27 March to 1800 UTC 28 March 2004 between 600 and 800 hPa (Fig. 7a). This maximum center was observed a few hours before the occurrence of high PV in the layers below 650 hPa (Fig. 5a). After 1800 UTC 28 March, the maximum center of the $P_{VPW}$ index disappeared, as did the high-PV layer in the lower troposphere. In stage II of cyclone A (Fig. 7b), the maximum center of the $P_{VPW}$ index with a peak value greater than 70% appeared at 850–950 hPa at 0000 UTC 31 March 2004, about 12 h prior to the PV maximum in the lower troposphere (Fig. 5b). In cyclone B, the large value exceeding 90% of the $P_{VPW}$ index in the layer of 850–950 hPa (Fig. 7c) appeared a few hours before the high-PV center in the lower troposphere (Fig. 5c). After 1800 UTC 16 January 2013, the value of the $P_{VPW}$ index dramatically decreased to 10%, coinciding with the weakening of the high-PV center in the lower troposphere (Fig. 5c). In cyclone C, the maximum value of the $P_{VPW}$ index had reached more than 70% around 600–850 hPa at 0000 UTC 24 November 2013 and over 90% at 1200 UTC 24 November (Fig. 7d). Again, the timing was prior to the PV maximum in the lower troposphere. All of these points offer strong evidence suggesting that the association of large PV values in the lower troposphere with the latent heating process. It is noteworthy that the vertical distribution of the high values of the $P_{VPW}$ index was similar to the PV profile mainly below the middle troposphere. In the middle and upper troposphere, high values of the $P_{VPW}$ index did not match with high values of PV. Therefore, only high PV in the
lower troposphere is mainly associated with latent heat release.

c. Near the surface

In the Northern Hemisphere, positive (negative) PV anomalies near the surface are associated with warm (cold) surface temperature anomalies, and the reverse can be said in the Southern Hemisphere (Hoskins et al. 1985). Figure 6 clearly indicates that this was observed in all three cases: namely, that near the surface large values of PV were associated with warm potential temperature. Here, we wish to add that, based on the PV dynamics [e.g., chapter 17 in Hoskins and James (2014)], the separation of the surface and lower-tropospheric high-PV center may become less visible if the latent heat release mainly takes place in the lower troposphere above the warm surface.

7. Conclusions

In this paper, we investigate three cases of explosively developing extratropical cyclones over eastern Asia by using ECMWF data. The focus of this paper is to examine the formation of PV towers during their explosive cyclogenesis phase. We name the first studied case cyclone A, which occurred from 26 March to 2 April 2004. This cyclone underwent explosive deepening processes twice. Its first explosive deepening (stage I, from 1200 UTC 26 March to 1200 UTC 30 March 2004) occurred over the land, and its second explosive deepening (stage II, after 1200 UTC 30 March 2004) occurred over the sea. The second studied case is named cyclone B. This cyclone had the strongest deepening rate among all three studied cases, taking place from 12 to 18 January 2013. It was generated over the eastern coast of the Philippine Islands, and its rapid deepening occurred in the extratropical zone, so it was regarded as an extratropical explosive cyclone (Hirata et al. 2015). The third studied case is named cyclone C, and its explosive development occurred from 24 to 26 November 2013.

Following Rossa et al. (2000) and Wang and Rogers (2001), we define a PV tower as a vertically aligned high-PV (≥1 PVU) region throughout the troposphere above a surface cyclone. Our analysis indicates that the formation of a PV tower coincides with the timing of the explosive cyclogenesis phase for each of the three cyclones. The vertical distribution of PV in a PV tower appears to have three centers: one in the middle and upper troposphere, one in the lower troposphere, and one near the surface. Although the high PV near the surface is not clearly separated from the one in the lower troposphere in all of the three cases, the high-PV region in the lower troposphere is distinctly separated from the high-PV region in the upper troposphere.

We examine the morphological characteristics of the upper-tropospheric PV. The common features of all three studied explosive deepening cases are a hook-shaped high-PV streamer wrapping counterclockwise around the center of surface cyclone on the southern and eastern sides and an arch-shaped low-PV tongue that wrapped the high-PV hook head from the north. The hook-shaped high-PV tongue overlaps with the maximum centers of both the relative vorticity and static stability parameter, indicating the stratospheric nature of the PV source inside the hook-shaped high-PV tongue. The high-PV region above the middle troposphere is due to the tropopause folding over the surface cyclone, as found in the literature (e.g., Reed and Danielsen 1958; Hoskins et al. 1985; Martin 1998).

The large PV near the surface appears to be associated with warm surface temperature anomalies, consistent with the PV dynamics (Hoskins et al. 1985). The large PV region in the lower troposphere is diabatically produced by latent heat release. Our results indicate that most of the high PV in the lower troposphere (about 70%–90% of the high-PV area) is concentrated in the area with abundant precipitable water. This is strong evidence suggesting an association of large PV values in the lower troposphere with the latent heating process. The latent heat release typically occurs near the middle troposphere, where the upward vertical motion is the strongest. Recall that the diabatic heating in the middle atmosphere would result in a PV dipole with negative PV anomalies aloft and positive PV anomalies below (Hoskins and James 2014). This explains why the high-PV region in the lower troposphere tends to be distinctly separated from the high-PV region in the upper troposphere.

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