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The structure and behavior of the arctic cyclone in summer analyzed by the JRA-25/JCDAS data

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Abstract

In this study, three-dimensional structures and the life-time behavior of arctic cyclones are investigated as case studies, using reanalysis data of JRA-25 and JCDAS. In recent years, arctic region has undergone drastic warming in conjunction with the reduced sea ice concentration in summer. The rapid reduction of the sea ice concentration is explained, to some extent, by a pressure dipole of the arctic cyclone and Beaufort high over the Arctic Ocean. This paper presents some case studies for the structure of the arctic cyclone.

It is found by the analysis of this study that the arctic cyclone indicates many differences in structure and behavior compared with the mid-latitude cyclone. The arctic cyclones move rather randomly in direction over the Arctic Ocean. The arctic cyclone has a barotropic structure in the vertical from the surface to the stratosphere. The arctic cyclone detected at the sea level pressure is connected with the polar vortex at the 500 hPa level and above. Importantly, the arctic cyclone has a cold core in the troposphere and a warm core around the 200 hPa level. The mechanism of the formation is discussed based on the analyzed structure of the arctic cyclones.

Keywords: Arctic cyclone; Polar vortex; Arctic weather

1. Introduction

In recent years, the Arctic has undergone a drastic change of warming. Rigor et al. (2000) suggested that surface air temperature (SAT) shows a significant warming trend during 1979–1997. The arctic surface has the positive ice-albedo feedback. Since the terminal of energy transport is in the arctic region and the vertical stability there is greater than that in the mid-latitudes, the warming in the Arctic is faster than the global average (Jones and Moberg, 2003; Zhang, 2005; Solomon et al., 2007). The, sea ice is most susceptible to the influence of global warming. Sea ice cover continued approximately flat before 1995 even though it varied seasonally. However, it has started to decrease since 1990s, and the extent in September 2007 was the lowest in ever recorded. This trend has been studied by various viewpoints. For example, the precipitation in the Arctic has been increasing and accession of Eurasian river discharge has changed the circulation and structure of the Arctic Ocean (e.g., McClelland et al., 2006; Pavelsky and Smith, 2006). Additionally, the intrusion of Atlantic waters into the Arctic Ocean accelerated the Atlantification and that caused many changes (Polyakov et al., 2005; Holland et al., 2006).

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Besides the long-term trends as presented above, it is suggested that the arctic cyclone has a strong impact to the environment (including sea ice) in the Arctic (see LeDrew, 1984). Murray and Simmonds (1995) showed that the arctic cyclone varies the exchange of fluxes of sensible and latent heat from the surface to the atmosphere and that modifies the sea ice extent. The arctic cyclone also enhances the surface wind speed and it leads the intensification of the surface stresses to sea ice and shifts the sea ice distribution. Maslanik et al. (1996) pointed out the importance of the relation between the reduction of the sea ice extent and the increase of frequency of the arctic cyclone during summer for 1978–1995. Moreover, it is mentioned that the arctic cyclone has the influences to the upper level heat budget and the structure of Arctic Ocean (e.g., Yang et al., 2001, 2004).

There are some studies about the arctic cyclone itself. Zhang et al. (2004) showed that the arctic cyclones are stronger in winter than in summer, by contrast the frequency and duration are greater in summer than in winter. It was shown that the generation of the arctic cyclone has various types, some of which occur in the arctic region, others come into the arctic region from mid-latitude (Simmonds et al., 2008). Furthermore, it was revealed that the former type is stronger than the latter type (Zhang et al., 2004), and both types tend to increase in recent years (Sepp and Jaagus, 2011). The generation mechanism of the cyclones in the Arctic was studied by Serreze et al. (2001) and Serreze and Barrett (2008). In their studies, the cyclones are generated at the arctic frontal zone constructed by the temperature contrast between the snow-free land and Arctic Ocean. This frontal zone becomes prominent during summer at northeast Eurasia, and it also appears at Alaska that stands out in summer. There are some important relations between the emergency of the prominent arctic frontal zone and the largest frequency of arctic cyclone during summer. In addition, they showed the most parts of the cyclones that generate in Arctic occur in Eurasian frontal zone.

As described above, there are some studies about the long-term trend in the strength and frequency of the cyclones, the relation to the environment in the Arctic, and the mechanism of the cyclogenesis. However, the three-dimensional structure of the arctic cyclone is not well described in the past studies. The purpose of this paper is to investigate the three-dimensional structure of the arctic cyclone and to compare it with the mid-latitude cyclone. In Section 2, the data used in this study and the analysis method are explained. Results are described in Section 3. Concluding remarks are presented in Section 4.

2. Method and data

The first step of the analysis is to identify all cyclones at the surface and to analyze the location of the center of the upper polar vortex. In order to detect the center of the cyclone and make the tracking data, we used the method by Aadachi and Kimura (2007). In this algorithm, four times daily sea level pressure (SLP) anomaly data from the climatological SLP data are utilized to remove the effect of the topography, and that anomaly data are linearly interpolated to 1.25° by 1.25° latitude/longitude version of the National Center for Geographic Information and Analysis (NCGIA) north polar Equal-Area Scalable Earth (EASE) grid. This algorithm detects cyclones with a diameter of over 20 km. Cyclone tracking employs a nearest-neighbor analysis approach, which compares the positions of the cyclone for a given 6-h chart with those of the next 6-h chart. The position of the upper air polar vortex is determined by the vorticity distributions at the 500 hPa level, although the analysis is conducted for all vertical levels at 850 hPa, 500 hPa and 200 hPa. Here, the vorticity ζ is represented by

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \qquad (1)$$

Here, u and v denote the zonal and meridional wind speeds. In this study, the sea level pressure, vorticity, temperature and vertical p-velocity data of the JRA-25 (Japanese 25-year Reanalysis) and JCDAS (JMA Climate Data Assimilation System; JMA: Japan Meteorological Agency) are used during the summer season (JJA) for 2005–2008.

The vorticity data used in the analysis are included in the JRA-25/JCDAS dataset. In order to adjust the influence of the density stratification in the vertical, vorticity is scaled using pressure as follows:

$$\zeta_{dc} = \zeta \times \sqrt{\frac{\rho}{\rho_s}} \times 10^5 = \zeta \times \sqrt{\frac{p}{p_s}} \times 10^5. \qquad (2)$$

The normalized vorticity with density correction applied is denoted by ζ_{dc}. Here, p represents pressure, ρ the density; subscript s represents the value at the standard level (1000 hPa).

3. Result of the analysis

All of the arctic cyclones occurred during each summer time from 2005 to 2008 are analyzed in Takahashi (2009). Fig. 1 illustrates cyclone tracks for the months of July 2006, July 2007, and June 2008. More

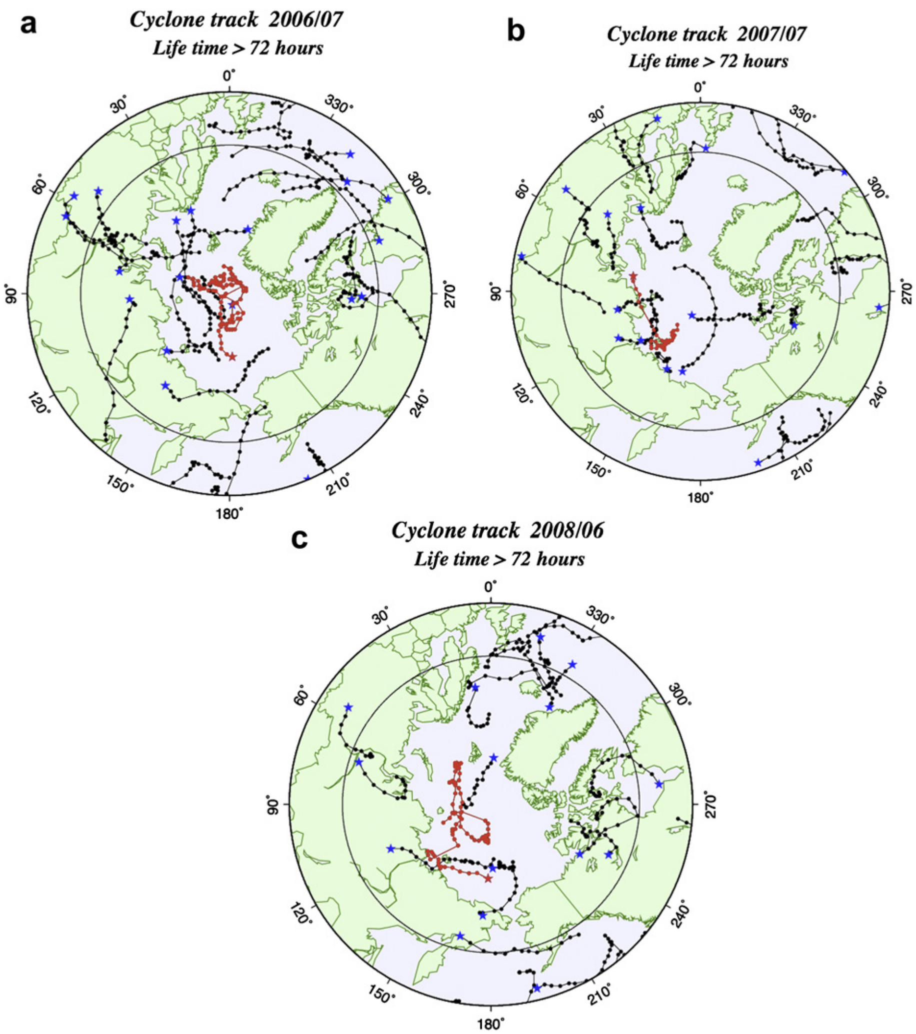

Fig. 1. Cyclone trucks for (a) July 2006, (b) for July 2007 and (c) for June 2008. Only cyclones with a life-time longer than 72-h are marked. The cyclones are detected every 6-h and the points of cyclogenesis are marked with stars. The red lines show the target cyclones referred to as Case 1 for 2006, Case 2 for 2007 and Case 3 for 2008, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than ten tracks with their life-time longer than 72 h are plotted in the figure. Some of them are recognized as mid-latitude cyclones moving into the Arctic. However, some of them are generated and terminated within the Arctic. We select three typical cases of the arctic cyclones, which were generated and terminated within the Arctic and persisted beyond the time scale of the mid-latitude cyclones. The red lines in Fig. 1 mark the target cyclones of Case 1, 2, and 3, respectively.

The Case 1 shows the cyclogenesis at 12Z on 27 July 2006 at 76.99°N/182.49°E. The Case 2 shows the cyclogenesis at 12Z on 31 July 2007 at 76.76°N/129.75°E. The Case 3 shows the cyclogenesis at 00Z on 10 June 2008 at 79.12°N/141.38°E. The cyclone in Case 1 was strongest at 12Z on 19 July 2006 and persisted for 28-days staying in the middle of Arctic Ocean. The cyclone in Case 2 was strongest at 06Z on 3 August 2007 and persisted for 11-days staying in the Arctic Ocean around East Siberian Sea. Although the persistency is not sufficient for this case, we selected it because of a great concern with the drastic reduction of the arctic sea ice in 2007. The cyclone in Case 3 was strongest at 06Z on 22 June 2008 and persisted for 20 days. These cyclones move rather randomly in direction for sufficiently longer period, indicating the characteristics of the arctic cyclone, which is distinctly different from the movement of the mid-latitude cyclones or tropical cyclones.

Fig. 2 illustrates sea level pressure and the 500 hPa height for the mature stages of the arctic cyclones for

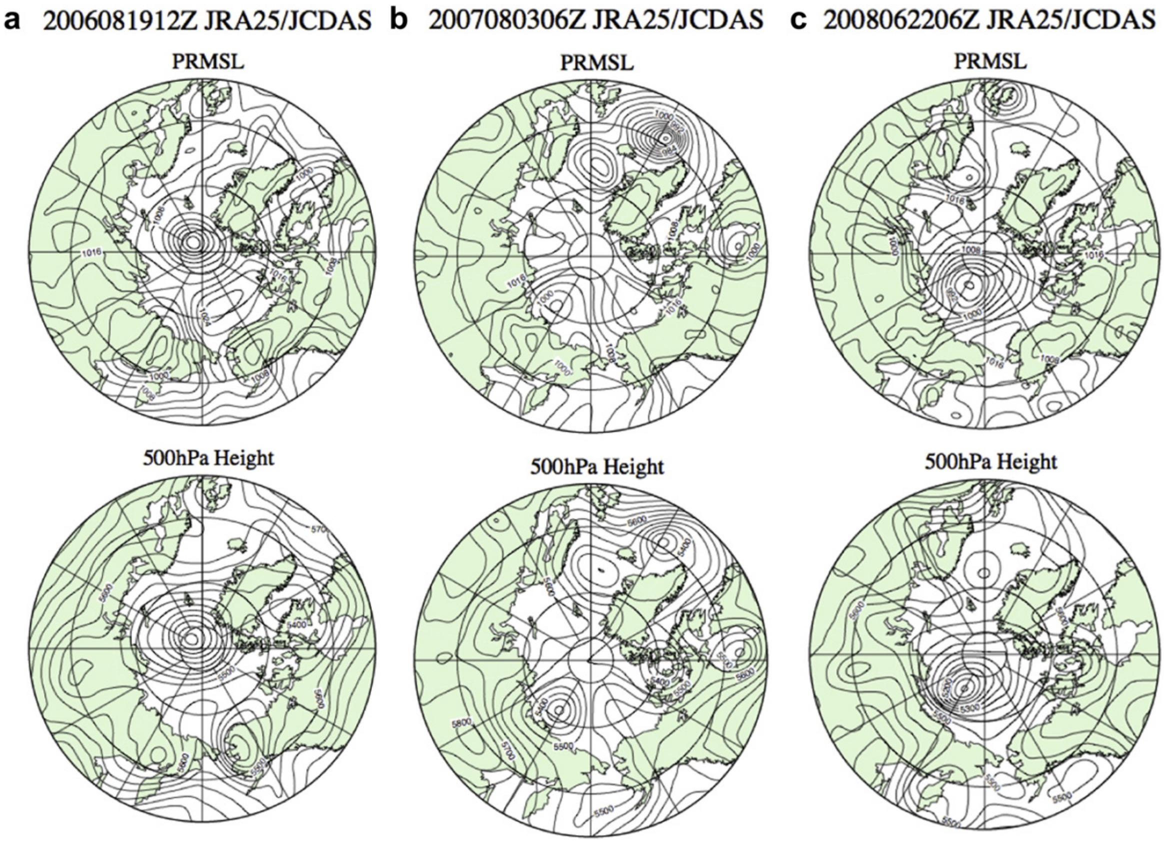

Fig. 2. Sea level pressure fields (hPa, top) and 500 hPa height fields (m, bottom) of the arctic cyclones for the Case 1 (a), Case 2 (b) and the Case 3 (c), respectively, analyzed with the JRA-25/JCDAS data.

Case 1–Case 3, respectively. In Case 1, the cyclone locates near the North Pole for both levels. The structure is almost barotropic in that the low-pressure center at the sea level is located just below the upper level vortex center. The depression at the 500 hPa height may be regarded as a polar vortex. In Case 2, the cyclone locates near the East Siberian Sea in the SLP field, and the low-pressure center of the 500 hPa height is located just above the surface cyclone. The Case 3 shows a pronounced cyclone at SLP in the center of Arctic Ocean. The 500 hPa height also shows the clear polar vortex just above the cyclone in SLP. These cases indicate the same feature that the arctic cyclone at the surface has a barotropic structure in the vertical direction and connected to the upper air polar vortex in the weather chart.

Figs. 3–5 illustrate relative vorticity at SLP, 850 hPa, 500 hPa and 200 hPa levels for the Case 1–Case 3, respectively. We applied the density correction for the relative vorticity by Eq. (2) in order to compare the intensity at different vertical levels. For the Case 1, a positive vorticity core is located near the North Pole for the surface arctic cyclone. The positive vorticity is clearly connected to the upper air vortex at 850 hPa, 500 hPa in the troposphere, and 200 hPa in the lower stratosphere. For the Case 2, a positive vorticity core is analyzed over the East Siberian Sea, corresponding to the surface arctic cyclone. We can find that the vortex tube extends upward at the same location up to 200 hPa. For the Case 3, a spiral shape of the positive vorticity is evident over the Arctic Ocean associated with the arctic cyclone detected in the SLP in Fig. 2. Since the arctic cyclone is an isolated vortex within the cold arctic air mass, the spiral shape of vorticity looks similar to the tropical cyclone which does not have a cold or warm front. The large pronounced vortex tube extends from the surface to the upper levels at 200 hPa. The round shape positive vortex at the 500 hPa and 200 hPa levels can define the polar vortex over the Arctic Ocean in summer.

Fig. 6 illustrates time variation of the vertical structure of the scaled relative vorticity above the center of the arctic cyclone averaged for the radius of 300 km for the Case 1–3. The vertical line in the figure

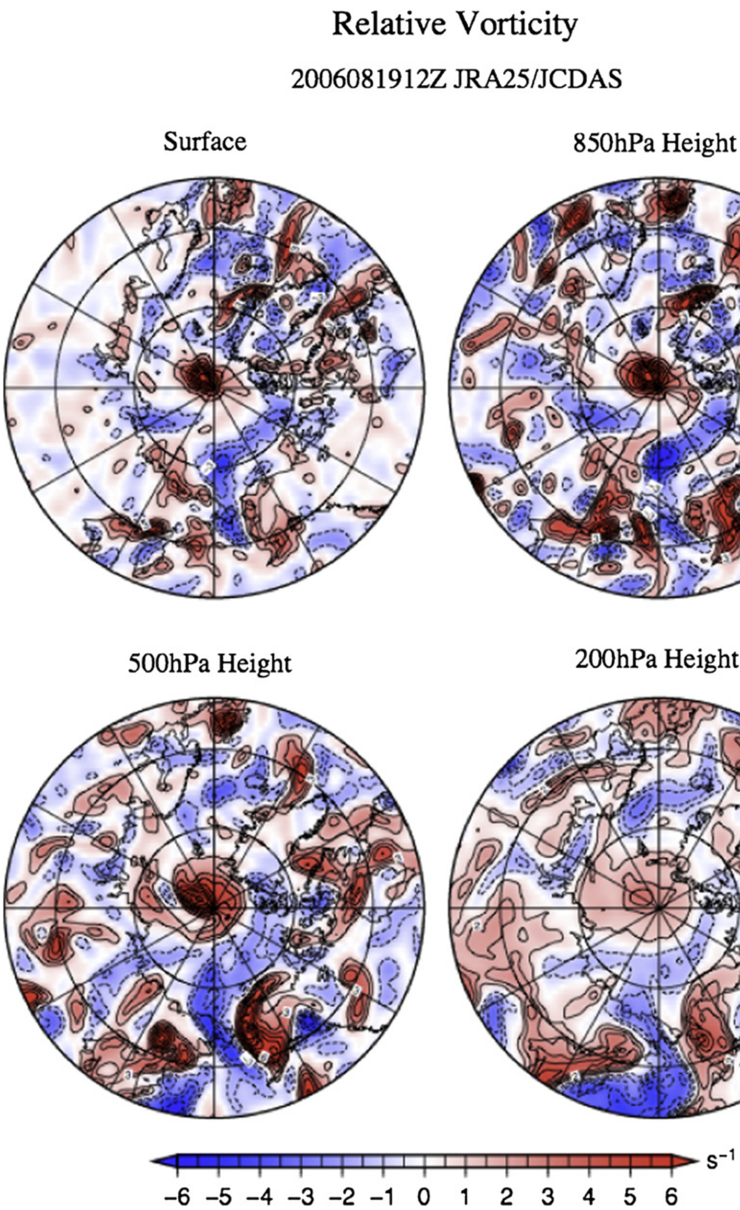

Fig. 3. Scaled relative vorticity for the Case 1 at SLP (top left), 850 hPa height (top right), 500 hPa height (bottom left) and 200 hPa height (bottom right). The red and blue colors show positive and negative vorticity, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

marks the date of the mature stage. For the Case 1, positive vorticity started on 28 July near the surface, then it extended upward. The scaled vorticity is approximately uniform in magnitude up to 200 hPa, but the maximum is seen near the 400 hPa level. The positive vorticity continues more than 27 day showing some interruptions and intensifications. For the Case 2, the vorticity shows a maximum near the 400 hPa level with some interruptions. For the Case 3, positive vorticity shows the peak near the 400 hPa level extending from the surface to the 200 hPa level. Occasionally some positive peaks appear near the surface, and they merge with the upper level peaks.

Fig. 7 illustrates vertical-time cross section of potential temperature anomaly from the climate above the center of the arctic cyclone averaged for the radius of 300 km for the Case 1–Case 3. The vertical line in the figure represents the mature stage of the surface cyclone. According to the results, it is found that the cold anomaly in the troposphere from the surface up to

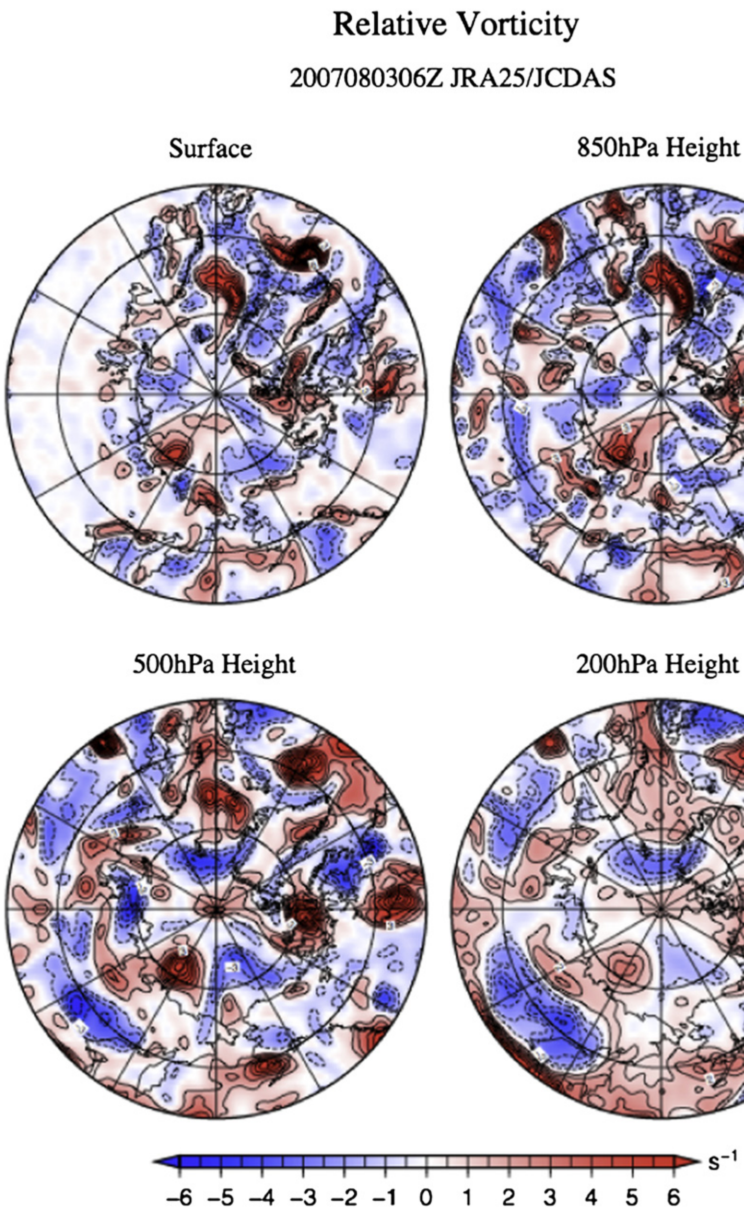

Fig. 4. Same as Fig. 3, but for the Case 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

300 hPa and the warm anomaly in the lower stratosphere above 300 hPa level are the common robust features of the arctic cyclone for all cases. The cold anomaly of the troposphere becomes warm anomaly near the lower surface especially for the Case 2 when the drastic sea ice melting occurred in 2007.

Fig. 8 illustrates vertical-time cross section of vertical motions above the center of the arctic cyclone averaged for the radius of 300 km for the Case 1−Case 3. The vertical line in the figure marks the date of the mature stage. Although the vertical motions are noisy with short time variations, we can detect dominant upward motions in the troposphere and persistent downward motions at the lower stratosphere above 300 hPa. Compared with the potential temperature anomaly in Fig. 7, we can recognize the upward motions at the cold core in the troposphere and the downward motions at the warm core in the lower stratosphere. The result implies the negative baroclinic conversion in energetics, which is distinctly different from the baroclinically unstable eddies in the mid-latitudes. Since the arctic cyclone persists more than

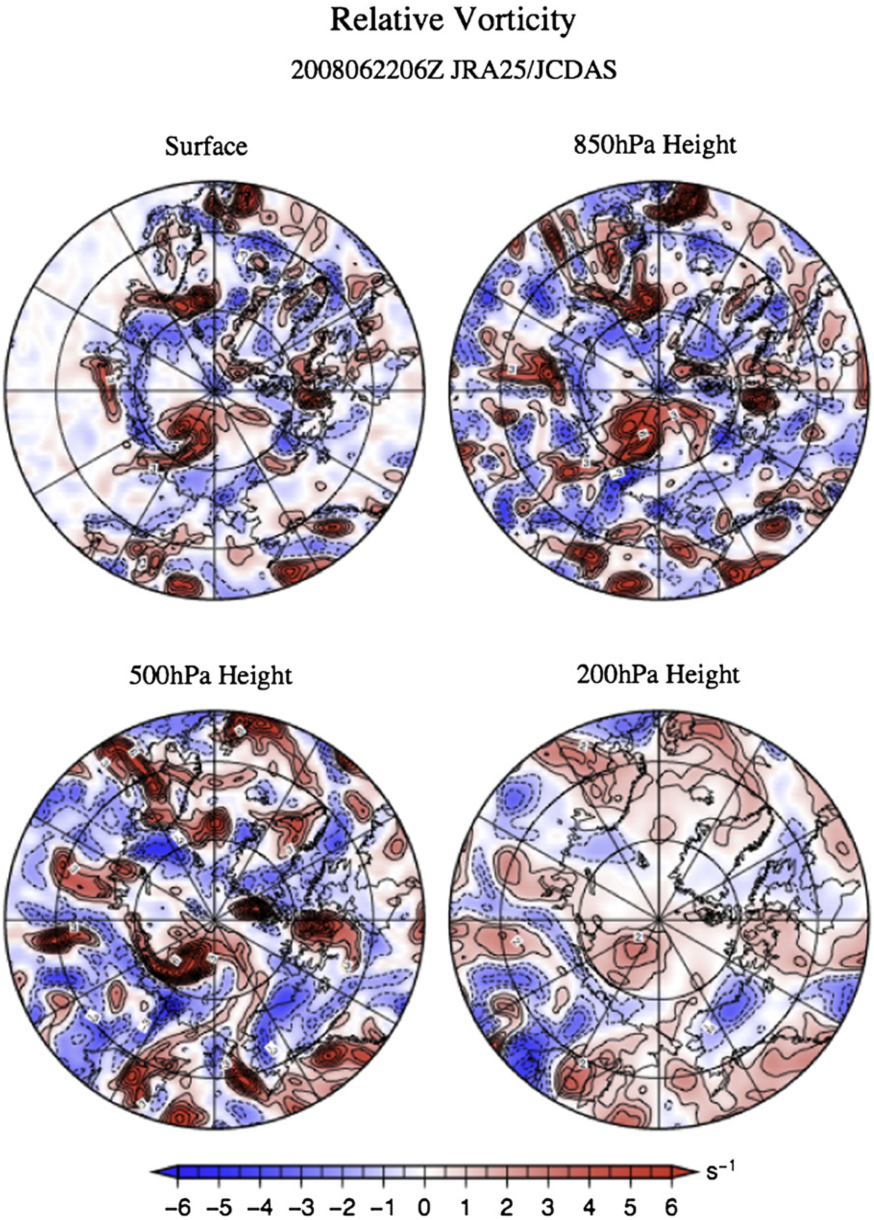

Fig. 5. Same as Fig. 3, but for the Case 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

20 days for Case 1 and 3 despite the negative baroclinic conversion, the result implies that the arctic cyclone is supported by a mechanism other than the baroclinic instability.

Fig. 9 illustrates the longitude-height cross section of the scaled relative vorticity across the center of the arctic cyclone during the mature stage for the Case 1–Case 3, respectively. Since the latitudes are high enough for all cases, the cross sections represent the vertical structure of the arctic cyclone along a small circle around the North Pole. The vertical line in the figure marks the location of the arctic cyclone. For all cases, surface vorticity is connected to the upper air vorticity in the troposphere and the vortex tube extends well into the lower stratosphere indicating a barotropic structure. The westward vertical tilt that is essential for the mid-latitude cyclone is not detected in the result. The polar vortex in summer extends from the surface up to 50 hPa level, and the easterly dominates above this level. Therefore, the surface arctic cyclone may be

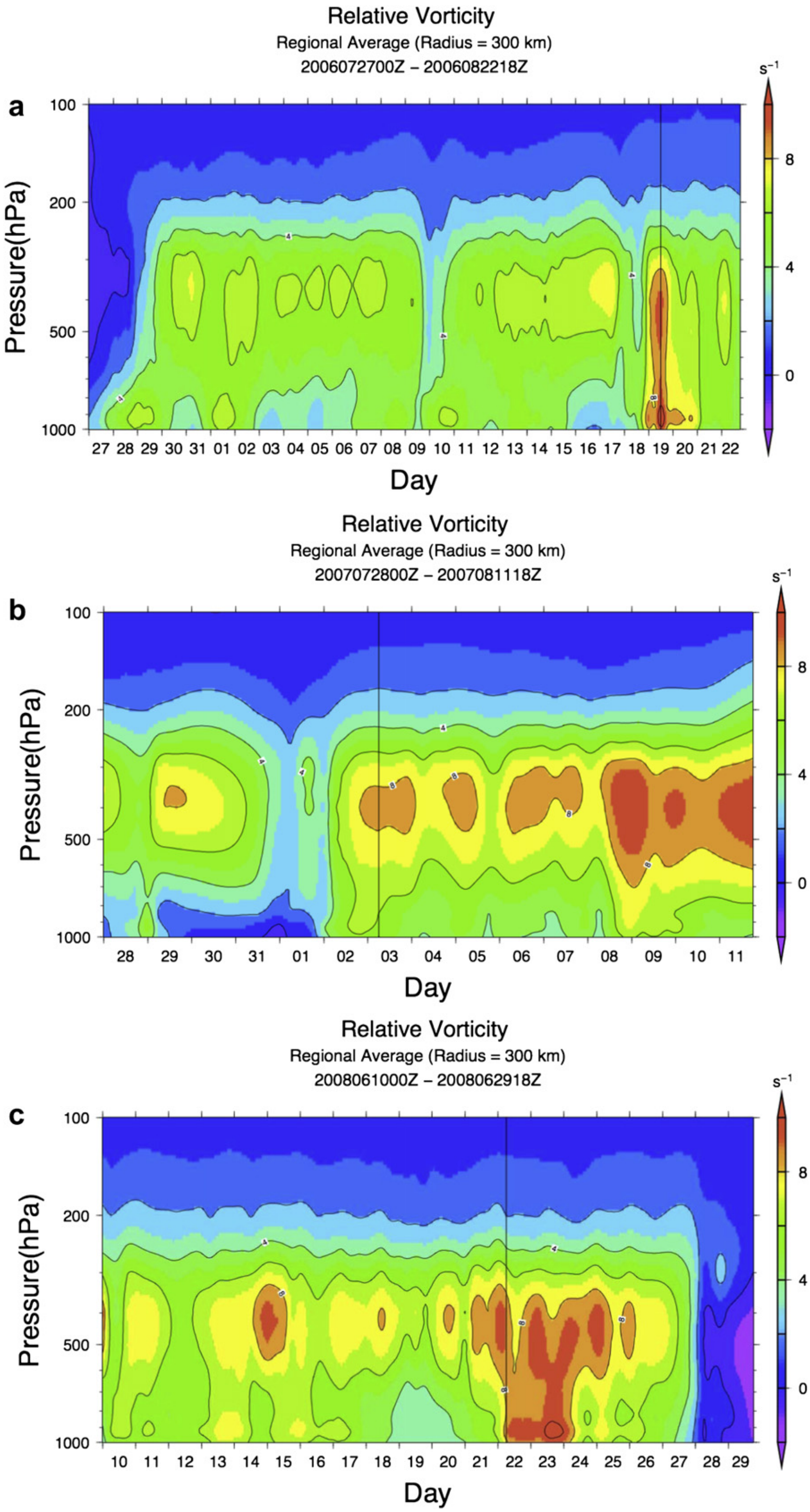

Fig. 6. Time series of the vertical cross sections of scaled relative vorticity above the center of the arctic cyclone averaged for the radius 300 km for the Case 1 (a), Case 2 (b) and the Case 3 (c), respectively. The mature stage of the life-cycle is marked by a vertical line.

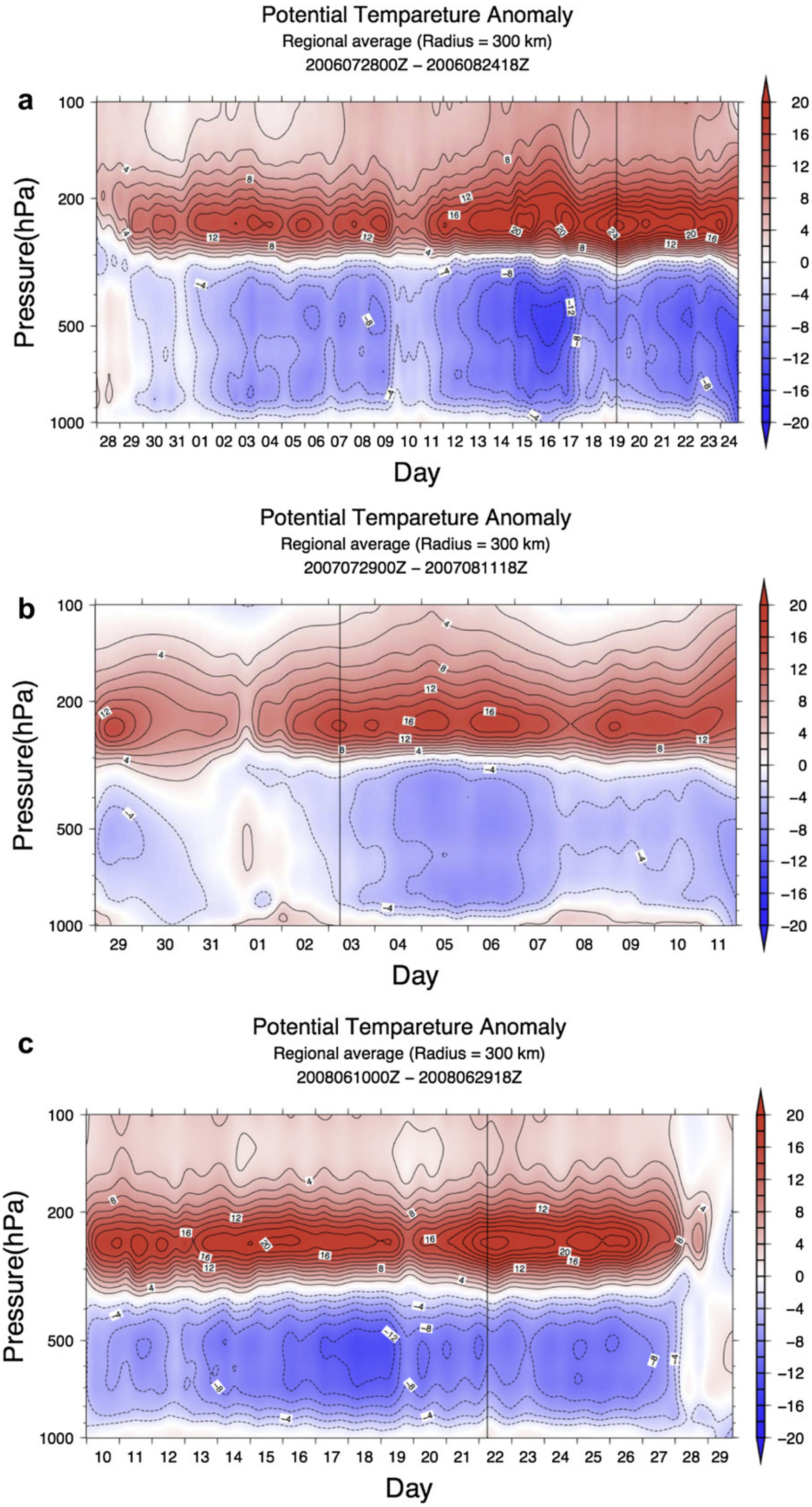

Fig. 7. Time series of the vertical cross sections of potential temperature anomaly above the center of the arctic cyclone averaged for the radius 300 km for the Case 1 (a), Case 2 (b) and the Case 3 (c), respectively. The mature stage of the life-cycle is marked by a vertical line.

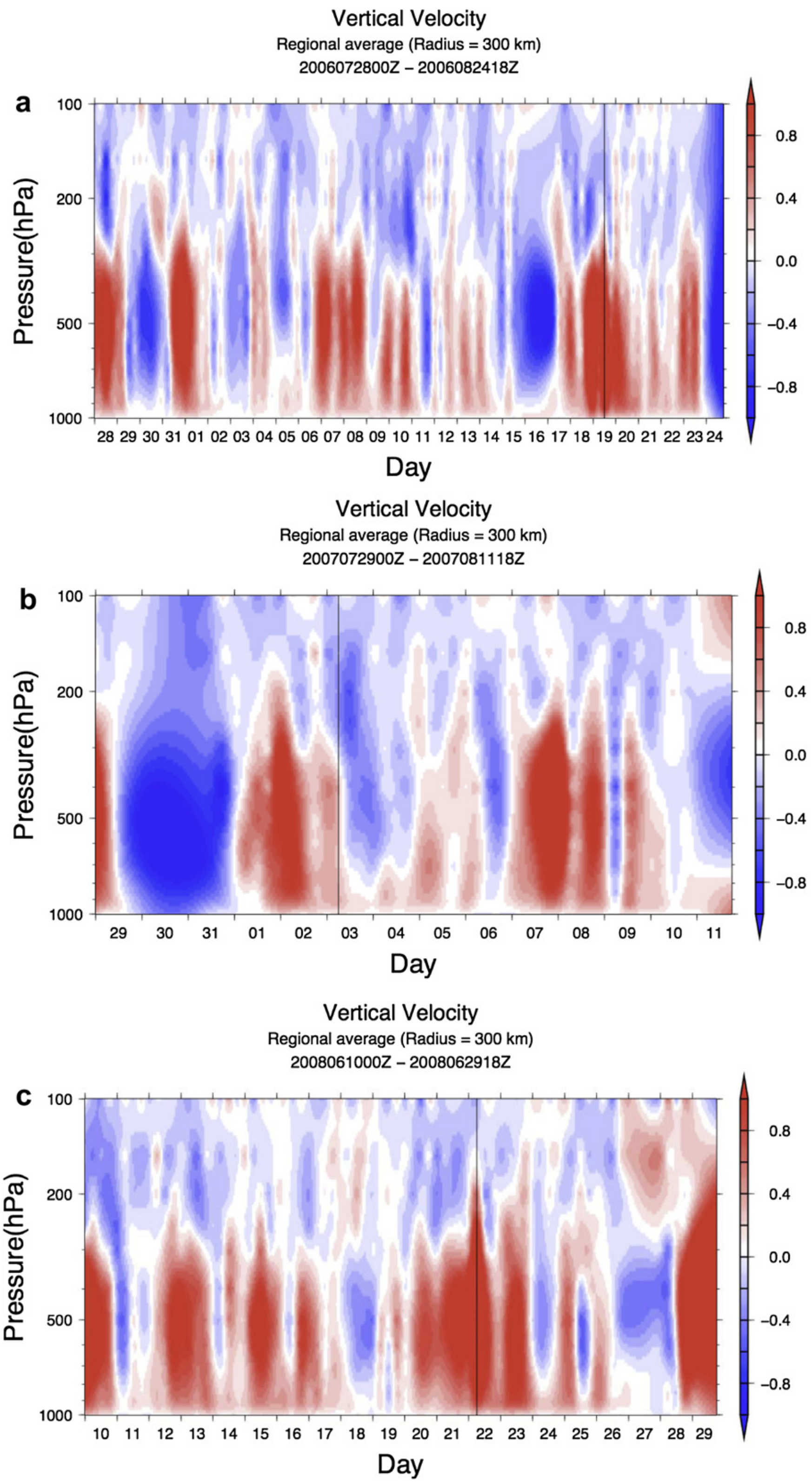

Fig. 8. Time series of the vertical cross sections of vertical motions above the center of the arctic cyclone averaged for the radius 300 km for the Case 1 (a), Case 2 (b) and Case 3 (c), respectively. The mature stage of the life-cycle is marked by a vertical line.

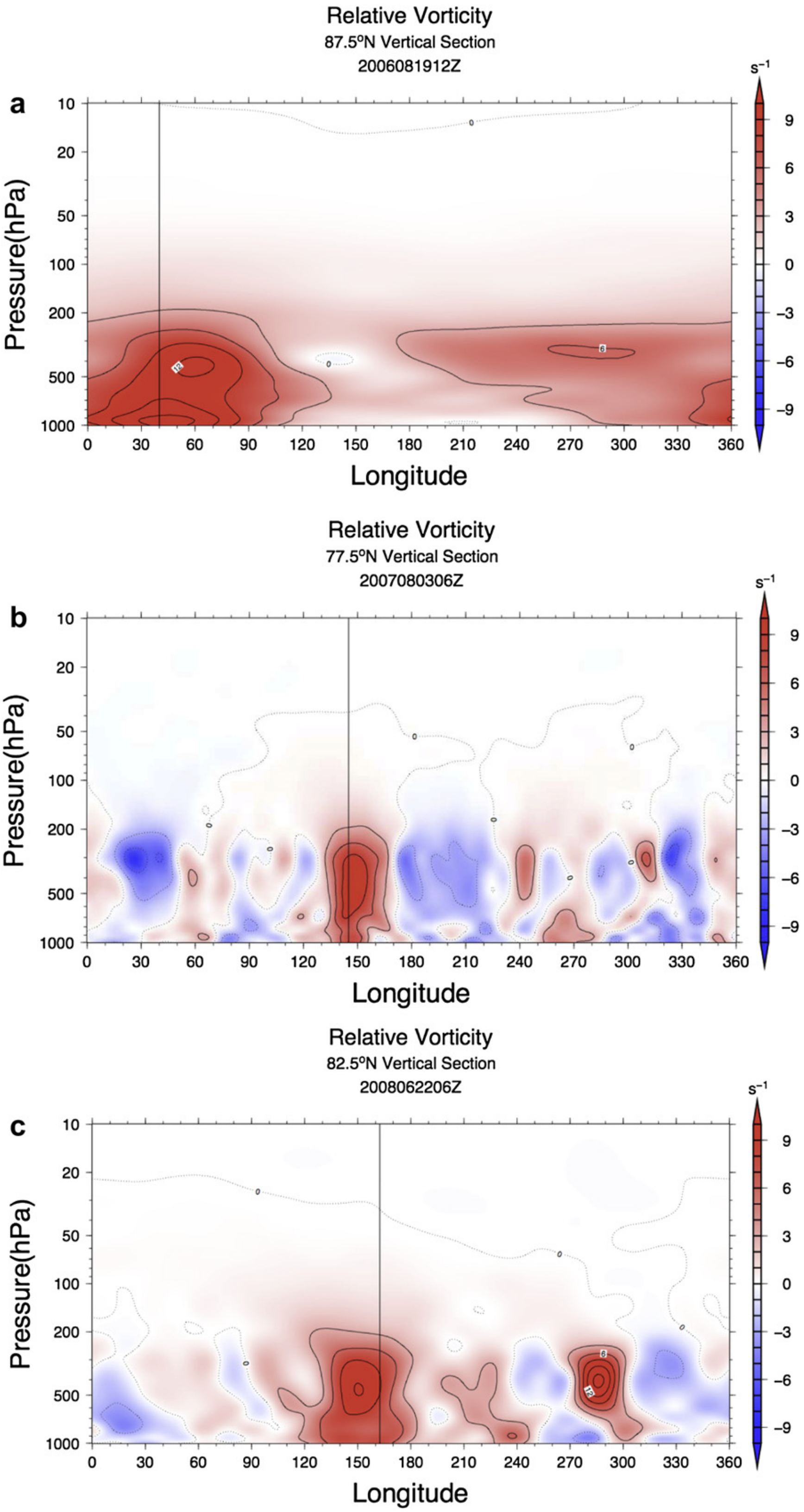

Fig. 9. Longitude-height cross section of scaled relative vorticity. Cyclone center is marked by a line at 40°E in Case 1 (a), 145°E in Case 2 (b) and 162.5°E in Case 3 (c). The values are scaled in colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

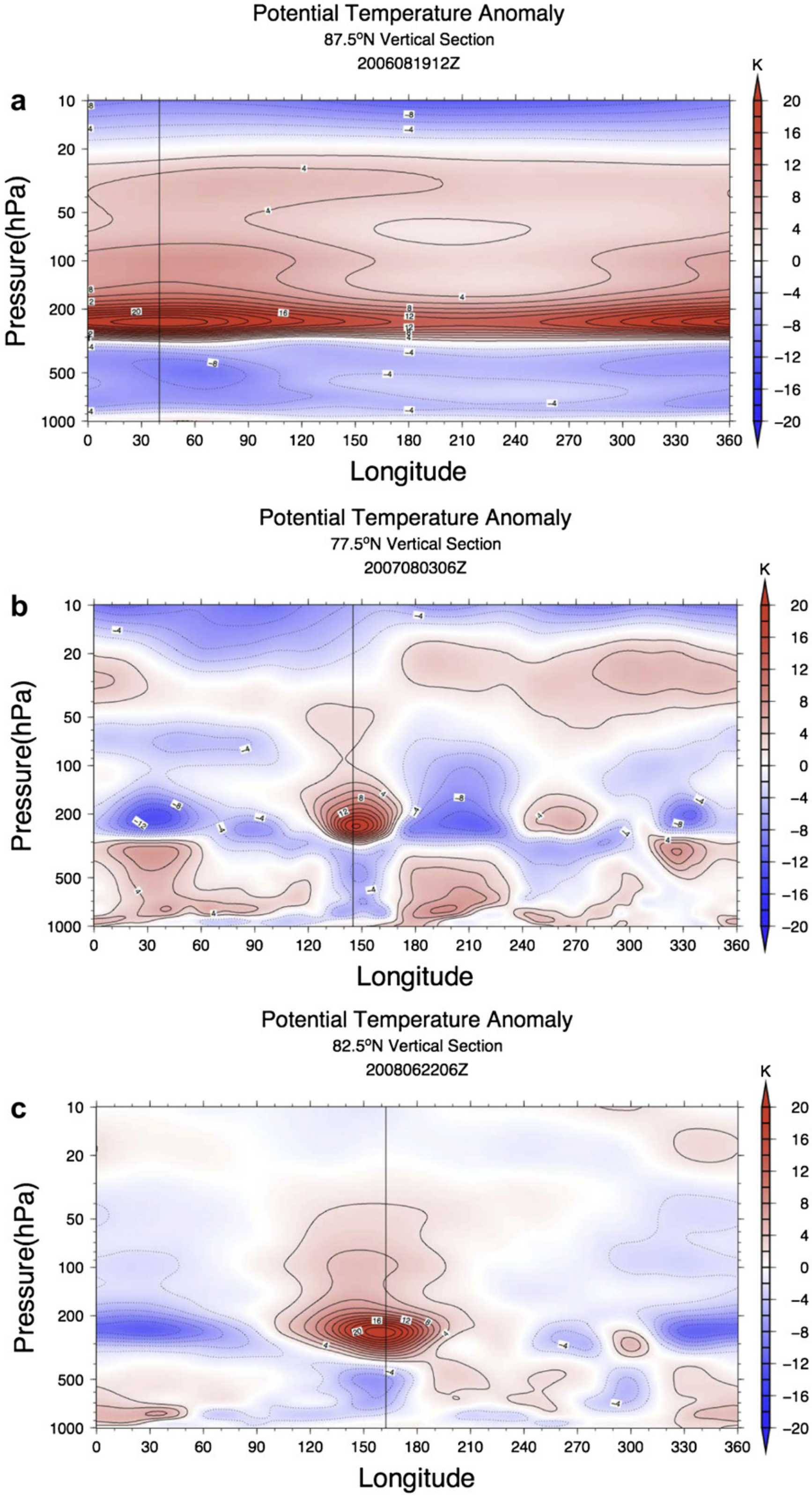

Fig. 10. Longitude-height section of potential temperature anomaly for the Case 1 (a), Case 2 (b) and Case 3 (c), respectively. The values are scaled in colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

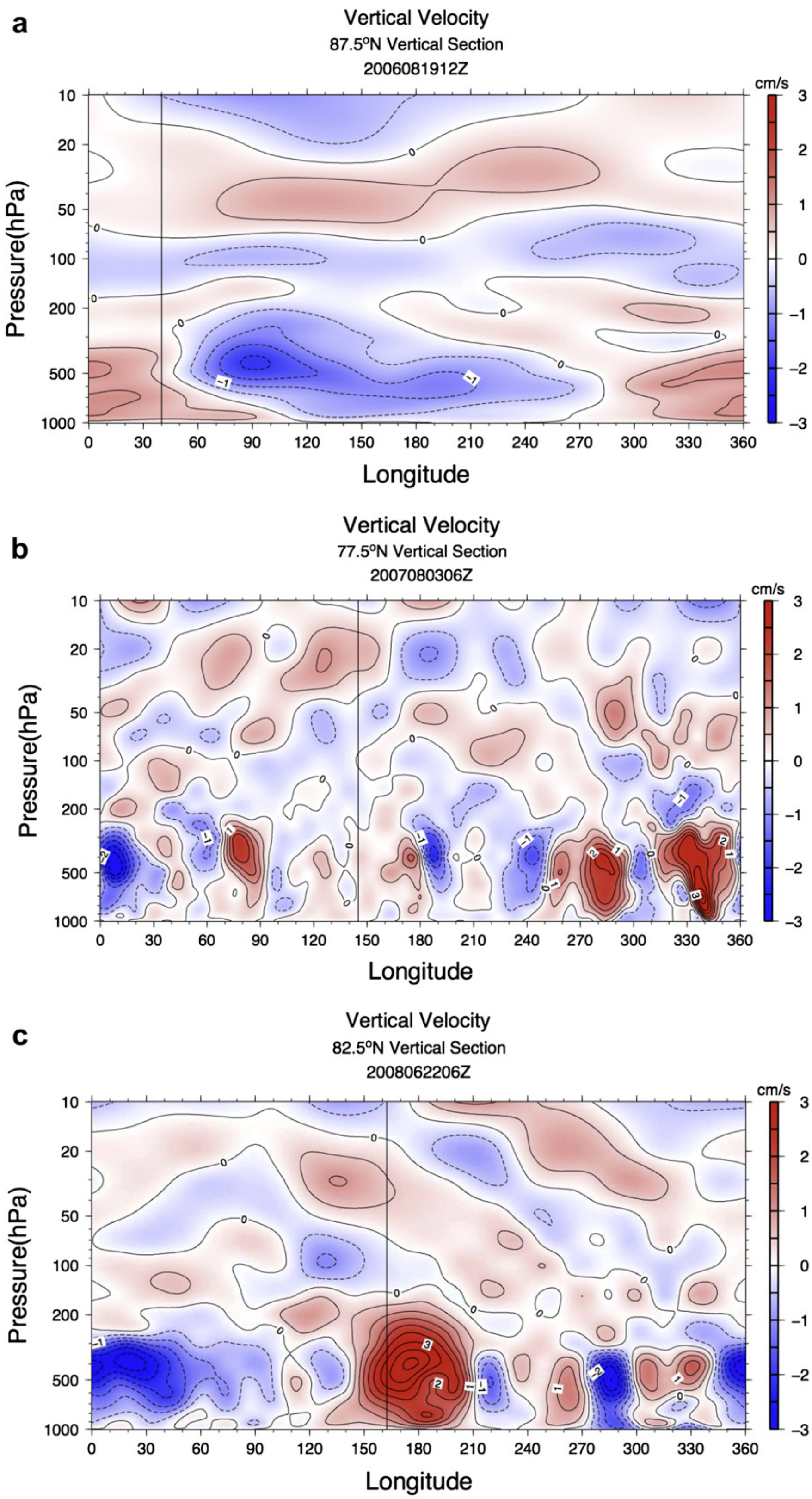

Fig. 11. Longitude-height cross section of vertical velocity for the Case 1 (a), Case 2 (b) and Case 3 (c), respectively. The values are scaled in colors.

recognized as a part of the polar vortex, which should have a different dynamics from the mid-latitude cyclone or tropical cyclone.

The positive vorticity of the arctic cyclone and the polar vortex is dynamically connected with temperature distributions. Fig. 10 illustrates the longitude-height cross sections of potential temperature anomaly from the climate along the center of the arctic cyclone as in Fig. 9 for the Case 1–Case 3, respectively. For the Case 2, the temperature anomaly represents a cold air mass over the arctic cyclone near 150°E in the entire troposphere, and a pronounced warm core is detected in the lower stratosphere. The warm core extends up to 30 hPa in the stratosphere. It is important to note that this cold core in the troposphere and the warm core in the lower stratosphere are essential to produce the vertical vortex tube of the polar vortex from the surface to the 30 hPa level. The center of the arctic cyclone in the troposphere is colder than the surrounding air mass, which is a marked difference from the mid-latitude cyclone or tropical cyclone. The structure is similar to the cold vortex of the cut-off low appearing near the surface. For the Case 3, the vertical cross section of potential temperature anomaly indicates the same characteristics as Case 2 with cold air mass at the center of the arctic cyclone within the troposphere, but a pronounced warm core in the lower to mid stratosphere.

Fig. 11 illustrates the same longitude-height cross section of vertical velocity for the Case 1–Case 3, respectively. While the temperature anomaly represents the same feature in all cases, the vertical velocity has different features because the figure is a snap shot at the mature stage of the surface arctic cyclone. In Case 3, the updraft is dominant in the entire level from the surface to the tropopause. It is reasonable to find upward motion near the surface due to the cyclonic vorticity with surface friction. Since the vertical motion varies rapidly, further statistical mean analysis may be required to detect the downdraft for the formation phase, mature phase, and decaying phase of the arctic cyclone.

4. Concluding remarks

In this study we examined the 3-dimensional structure of cyclones in the Arctic region as case studies using JRA-25/JCDAS reanalysis dataset. Some of the cyclones freak within the Arctic Ocean showing the life-time from cyclogenesis to cyclolysis longer than that of mid-latitude cyclones. It is known that the structure is highly barotropic with standing vortex tube in the troposphere to the lower stratosphere. Since the cyclone stays in the same Arctic air mass, there is no apparent cold or warm front around the vortex, but the vortex is surrounded by spiral cloud bands like a tropical cyclone. Such a cyclone over the Arctic Ocean having those features is referred to as “arctic cyclone”.

In this study we chose three typical arctic cyclones appeared in July 2006, July 2007 and June 2008, and conducted case studies. These arctic cyclones have a common structure in many aspects. First, these cyclones move around the Arctic Ocean in random direction since there is no prevailing westerly or easterly in the Arctic. Second, the height field shows the barotropic structure with a low-pressure center from the surface to the stratosphere. The arctic cyclone seen in the SLP field is connected to the polar vortex at 500 hPa height and above. The relative vorticity also shows the barotropic structure with a consistently standing vortex tube. The positive vorticity near the surface connects with the positive vorticity of the upper air polar vortex, and that vortex tube reaches to the 50 hPa level. According to these structures, the arctic cyclone is clearly coupled with the polar vortex. The cyclone at SLP develops by the coupling with the upper level polar vortex. The movement of the polar vortex may determine the random tracks of the surface cyclone. The barotropic structure of the vortex without a cold or warm front suggests that the arctic cyclone has a different exciting mechanism from the mid-latitude cyclone.

The vertical structure of the temperature anomaly suggests that the arctic cyclone has a robust warm core at the lower stratosphere above 300 hPa. This warm core is a unique feature of the formation and maintenance of the arctic cyclone. One of the possible origins of the warm core is a transport of warm air mass from lower latitudes carried by the mid-latitude cyclones. However, the long-lived warm core requires another maintenance mechanism. The polar vortex in summer is produced not only by the local thermal effect, but also by the general circulation of the atmosphere. The north–south temperature gradient, although weaker than winter, excites the upper air westerly generating the polar vortex core centered at the North Pole. The northward eddy heat transport emanates the vertical EP flux, which ultimately drives the meridional residual circulation to produce a downdraft over the Arctic. The warm core in the lower stratosphere may be associated with this downdraft over the Arctic.

Therefore, we find in this study that the coldest air mass over the Arctic Ocean drives a cold core vortex near the surface. The structure is similar to a cold vortex of the cut-off low in mid-latitudes. The arctic cyclone may be regarded as a cold vortex appearing near the surface in the Arctic. According to the analysis result of the vertical section of vertical velocity, we find upward motion from the surface to 300 hPa and weak downward motion above the 300 hPa levels.

We conducted a parallel study for the arctic cyclone using a cloud resolving global model called NICAM. The result clearly supports the existence of downward motion in the lower stratosphere above the arctic cyclone. The unique feature of the arctic cyclone which is distinct from the baroclinically unstable mid-latitude cyclone is the barotropic structure without the baroclinic conversion. The low-level vortex of the arctic cyclone is coupled with the upper air polar vortex in the vorticity field, and the cold core of the arctic cyclone is accompanied by upward motions. The arctic cyclone moves around the Arctic Ocean and survives longer time than the mid-latitude cyclones. The origin of the arctic cyclone is not the baroclinic instability, but the merging of smaller scale meso-cyclones like the tropical cyclones. The warm core in the lower stratosphere is not maintained by the latent heat of condensation, but the adiabatic heating due to the downdraft in the stratosphere. The vorticity supply by the upper polar vortex is another important mechanism to maintain the arctic cyclone which is different from the mid-latitude cyclone. We believe that all these features are worth to discuss as an important feature of the arctic cyclone.

We need to investigate further about the relation between the surface arctic cyclone and the upper air polar vortex. Since some kinds of cyclogenesis are seen outside of the arctic frontal zone as suggested by Serreze and Barrett (2008), the relation between the arctic cyclone and the mid-latitude cyclone is another important subject in the future.

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