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Characteristics of Atmospheric Circulation Associated with Cold Surge Occurrences in East Asia: A Case Study During 2005/06 Winter

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ABSTRACT

The characteristics of the upper-level circulation and thermodynamical properties for the period when two distinct cold surges broke out over East Asia during the 2005/06 winter are investigated. From early December 2005 to early January 2006, exceptionally cold weather lasted for approximately one month due to two successive cold surges that took place on 2 December 2005 and 2 January 2006, respectively. This study reveals that both involve the upper-tropospheric circulation, which induces the amplification and expansion of the surface Siberian high toward East Asia, but arose from different causes: the former is caused by the upper-level blocking originated from the North Pacific and the latter is caused by the upper-level wave train across the Eurasian Continent. In particular, it is suggested that the lower-tropospheric anomalous wind caused by upper-level circulation anomalies and a steep meridional temperature gradient amplified by phase-locked annual cycle combined to induce very strong cold advection in East Asia, which resulted in exceptionally cold weather that lasted for several weeks. The present results emphasize that the characteristics of the upper-tropospheric circulation can be considered as important precursors to cold surge occurrences in East Asia.

Key words: cold surge, Siberian high, East Asia, East Asian winter monsoon, upper-tropospheric circulation

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1. Introduction

As a conspicuous phenomenon of the East Asian winter monsoon (EAWM) circulation, the cold surge has tremendous impacts on social and economic activities. A cold surge comprises a steep increase in the surface pressure, the prevailing northwesterly winds, and resulting strong cold advection toward East Asia which leads to a sharp temperature drop within a few days. Every winter, more than ten cold surges, which originate from the deep interior of the Eurasian Continent (Boyle and Chen, 1987; Chen et al., 2004), sweep across East Asia and bring extreme cold weather. It often causes heavy snowfall along the coastal regions in East Asia (Boyle and Chen, 1987; Ding, 1994; Chen, 2002) and further induces strong convective activities over the South China Sea; the latter accelerates the local Hadley circulation (Chan and Li, 2004; Neale and Slingo, 2003).

Many studies have investigated the outbreak and development mechanisms of cold surges (e.g., Lau and Lau, 1984; Zhang et al., 1997; Chen, 2002, Jeong et al., 2008). In the viewpoint of large-scale climate in East Asia, a cold surge occurrence can be manifested by the abrupt expansion of the Siberian high toward East Asia. Hence, the intraseasonal modulation of the Siberian high is known to be the most critical factor (Zhang et al., 1997; Gong and Ho, 2002,

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2004; Takaya and Nakamura, 2005a,b) for its initiation. The Siberian high is a semi-permanent cold-core high-pressure system maintained by strong diabatic cooling at the surface and large-scale subsidence motion (Ding and Krishnamurti, 1987). Occasionally, particular upper-tropospheric disturbances can induce its amplification and expansion and the best-known feature of those disturbances is the shortwave train over Lake Baikal, which induces strong cold advection underneath to strengthen the surface anticyclone (Lau and Lau, 1984; Chen, 2002). The shortwave train further intensifies the East Asian trough, which induces the strengthening of the northeasterlies in the lower troposphere (Joung and Hitchman, 1982; Lau and Lau, 1984; Boyle and Chen, 1987; Takaya and Nakamura, 2005b).

Recently, Takaya and Nakamura (2005a,b) have suggested two typical types of distinct upper-level circulations, one originating from the Pacific Ocean and the other from the Atlantic Ocean, that amplify the Siberian high and tend to cause cold air outbreaks in East Asia. Jeong et al. (2006) suggested a further connection of such lower-stratospheric precursory signal to lower stratospheric disturbance, the large-scale negative potential vorticity (PV) anomalies over Siberia that induces the upper-tropospheric wave source which give rise to a baroclinic growth and leads to the amplification of the Siberian high. It has also been suggested that several other large-scale circulation fields affect the occurrence of cold surges. The strength of the EAWM is directly proportional to the strengths of the surface northeasterlies, Siberian high, Aleutian Low, and East Asian coastal trough, all of which are favorable conditions for the frequent occurrence of cold surges. Therefore, the interannual or interdecadal variations of the EAWM circulation considerably influence cold surge occurrences (e.g., Lau and Lau, 1984; Lau and Lau, 1984; Zhang et al., 1997).

Previous studies have documented the modulation of cold surge occurrence by the Arctic Oscillation (AO; Thompson and Wallace, 1998), and the remote influence of the ENSO and the Madden and Julian Oscillation (MJO; Madden and Julian, 1971). Jeong and Ho (2005) reported that large-scale anomalies in the negative AO phase provide a strong Siberian high and favorable upper-tropospheric circulation for a cold surge outbreak. With regard to remote influences from tropical variabilities, Zhang et al. (1997) suggested that the remote modulation of the Siberian high by the ENSO affects cold surge occurrences through the interannual variation of winter northerlies near the South China Sea. Chen et al. (2004) suggested that the upper-level shortwave train over East Asia and the northwest Pacific modulated by the North Pacific ENSO shortwave train can affect cold surge occurrences. Jeong et al. (2005) showed that extreme cold surges often occur when the convective center of the MJO is located over the Indian Ocean because the MJO-induced large-scale extratropical changes reinforce the amplification of cold surges. In addition, Jeong et al. (2008) proved that the MJO-related cold surges modulate winter rainfall over East Asia.

These studies have revealed the importance of upper-level circulations on the intensification of the Siberian high during cold surge occurrences by employing theoretical analyses and/or statistical evidences. In this study, we attempt to apply these understandings to a practical case, which is essential for its application in weather forecasting. In the wintertime of 2005/06, East Asia underwent an extraordinary cold period for approximately one month from early December 2005 to early January 2006; starting on 2 December 2005, the extremely cold weather overwhelmed most of East Asia and lasted for several weeks. The climatological value never recovered during this period, and the cold weather was prolonged until the subsequent cold surge event that occurred on 2 January 2006. Interestingly, the characteristics of the two cold surges represent quite distinctive features, particularly with regard to the upper-tropospheric circulations during their developing stages; these circulations strikingly resemble the evolution patterns introduced by Takaya and Nakamura (2005a,b). In the present study, we performed dynamical interpretation of the evolution of the upper-level signal that caused the subsequent intensification of the Siberian high. The related thermodynamical changes and large-scale features are also considered.

This paper is organized as follows. A description of the data used and the analysis techniques in addition to the determination of cold surges, the calculation of the isentropic potential vorticity, and thermodynamical interpretation are given in section 2. In section 3, the overall large-scale features during the 2005/06 winter, the precursory upper-level circulation, and the subsequent development of two distinctive cold surges are presented. The findings of the present study are summarized in section 4.

2. Data and analysis method

2.1 *Data*

The daily mean surface air temperatures (SAT) from 188 Chinese and 7 Korean stations obtained from the China Meteorological Administration and the Korea Meteorological Administration, respectively, for the period from November 2005 to February 2006 are used. The daily mean temperature, geopotential height, horizontal and vertical wind data, and mean sea level pressure (MSLP) are obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996). The data have a horizontal resolution of 2.5° × 2.5° in longitude and latitude and 17 pressure levels ranging from 1000 hPa to 10 hPa. Monthly optimum interpolation SST data on a 1° × 1° longitude-latitude grid is obtained from the National Oceanic and Atmospheric Administration (NOAA) (Reynolds et al., 2002).

Two large-scale indices, the AO and Siberian high, which are known to influence cold surges are examined. The daily AO index estimated by the EOF analysis of the geopotential height at 1000 hPa is taken from the NOAA website (http://www.cpc.noaa.gov/products/precip/Cwlink/all_index.html). The intensity of the Siberian high is defined by the domain average of the MSLP over 40°–60°N and 80°–120°E, where the center of the quasi-stationary continental high-pressure system lies during winter. This definition is similar to that of previous studies (e.g., Gong and Ho, 2002; Wu and Wang, 2002; Jeong and Ho, 2005).

To focus on the intraseasonal variation of the upper-level changes and its modulation of the intensification of the Siberian high at the surface, an eight-day low-pass Lanczos filter (Lanczos, 1956) is applied to the reanalysis data sets.

2.2 *Determination of cold surges*

The present study mainly focuses on the evolutions of two cold surges during the 2005/06 winter. The occurrence days of the two cold surges are determined objectively based on the synoptic criteria of the SAT drop and the expansion of the Siberian high; this determination process has been slightly modified as compared to the previous studies of Zhang et al. (1997) and Jeong and Ho (2005). A cold surge occurrence is detected when the day-to-day drop in the SAT (i.e., T_{day} minus $T_{\text{day-1}}$) averaged over the stations to the east of 105°E (total 137 stations) exceeds a standard deviation of −1.5 for 3 consecutive days when the intensity of the Siberian high is larger than one standard deviation. To calculate the SAT drop for 3 consecutive days, a 3-day running mean is performed within ±1 day. Given this determination, three cold surge occurrences are identified in the 2005/06 winter: 2 December 2005, 2 January 2006, and 1 February 2006 (see Fig. 1a). During 2005/06 winter there were three events of strong SAT drop but not determined as a cold surge event, because the Siberian high was not so strong at that time. We have checked the synoptic environment for those periods and found that those SAT drops are mostly induced by northerly winds related to a fast propagating synoptic system, not with a large-scale phenomenon involving an expansion of the Siberian high. Thus, the duration of cold weather is not so long as compared to cold surge cases in those comprising the amplification of the Siberian high.

2.3 *Isentropic potential vorticity*

The isentropic potential vorticity (IPV) is evaluated to infer the upper-level influence on the amplification of the Siberian high at the surface. The IPV is a powerful factor and is widely used for diagnosing the dynamical and thermodynamical properties of a synoptic weather system, particularly for diagnosing upper-level influences on the surface flows because of its conservative and invertible properties. Following the methodology of Hoskins et al. (1985), the PV on the isobaric coordinate is first evaluated by using the expression

$$\mathrm{PV} = -g(f\boldsymbol{k} + \nabla_{\mathrm{p}} \times \boldsymbol{V}) \cdot \nabla_{\mathrm{p}}\theta \,, \tag{1}$$

where g is the gravitational acceleration; f, the Coriolis parameter; ∇_{p}, the pressure gradient operator; $\boldsymbol{k}$, the three-dimensional wind vector; and θ, the potential temperature. Subsequently, a linear interpolation on constant-θ surfaces yields the IPV defined as

$$\mathrm{IPV} = -g(f + \boldsymbol{k} \cdot \nabla_{\theta} \times \boldsymbol{V})\frac{\partial\theta}{\partial p} \,. \tag{2}$$

2.4 *Thermodynamical consideration*

The dynamical interpretation of the upper-level circulations using the PV values is able to reveal the lower-level amplification of the Siberian high, but a corresponding thermodynamical process in the lower troposphere, particularly strong cold advection near the surface, is essential to lead to a cold surge occurrence (Takaya and Nakamura, 2005b). We estimate the thermal advective terms of the temperature tendency during the cold surge occurrence using the wind and temperature at the lowest sigma level ($\sigma_{0.995}$) of the NCEP/NCAR reanalysis. Assuming $d\sigma/dt = 0$, the anomalous potential temperature tendency is decomposed as

$$\frac{\partial\theta'}{\partial t} = \underbrace{-\boldsymbol{V}' \cdot \nabla\bar{\theta}}_{\text{(a)}}\underbrace{-\overline{\boldsymbol{V}} \cdot \nabla\theta'}_{\text{(b)}}\underbrace{-\boldsymbol{V}' \cdot \nabla\theta'}_{\text{(c)}} + \mathrm{VA} + Q' \tag{3}$$

at $\sigma_{0.995}$. Here, the overbar and prime denote the climatological mean (i.e., basic state) and anomaly (i.e., deviation from the basic state), respectively. VA is the horizontal wind vector; ∇, the horizontal gradient operator; VA, the vertical advection terms; and Q',

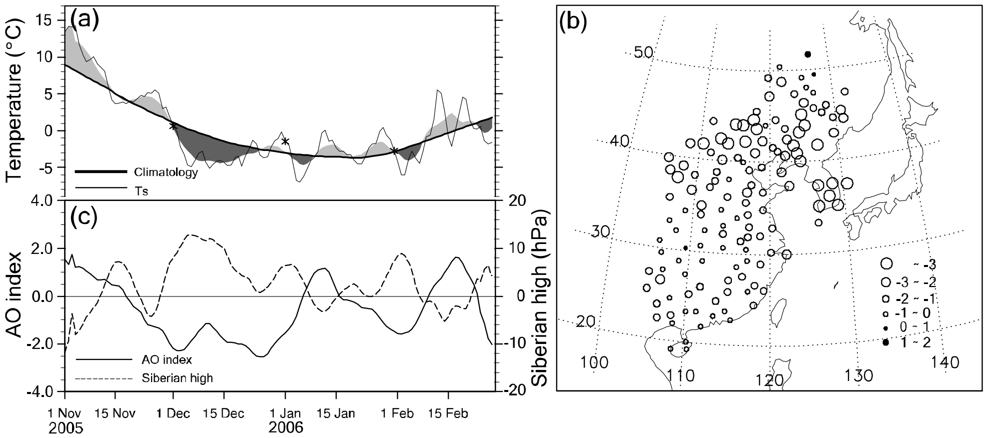

Fig. 1. (a) Time series of daily mean SAT (thin line) and its climatology (thick line) over East Asia during 2005/06 winter (from 1 November 2005 to 28 February 2006). The difference between day ±3 moving averages of temperature and climatology is shaded (positive and negative values are shown using light- and dark-grey shades, respectively). Asterisks indicate cold surge outbreaks in East Asia. (b) Spatial distribution of daily-mean SAT anomaly averaged from 2 December 2005 to 10 January 2006. (c) Time series of AO index (solid line) and the Siberian high index, i.e., MSLP averaged over 30°–45°N and 80°–120°E and (dashed line), during the same period mentioned in Fig. 1a. The day ±3 moving average is used.

the anomalous diabatic heating. Neglecting the small contributions by the vertical advection and diabatic heating terms in Eq. (3), the tendency term on the left-hand side and the three advective terms (a–c)—the basic-state temperature advection by the anomalous wind ($-\boldsymbol{V}' \cdot \nabla\bar{\theta}$), the anomalous temperature advection by the basic-state wind ($\overline{\boldsymbol{V}} \cdot \nabla\theta'$), and the anomalous temperature advection by the anomalous wind ($-\boldsymbol{V}' \cdot \nabla\theta'$)—on the right-hand side are evaluated in this study.

3. Results

3.1 *Overview of large-scale features during 2005/06 winter*

Figure 1a depicts the overall variation of the SAT during the 2005/06 winter together with the 1971–2000 climatology over East Asia. The occurrence days of the three cold surges are marked by asterisks in the figure. The most notable feature is the extremely cold period sustained for almost one month from early December to early January. Considering the typical timescale of cold surges, which is 5–14 days (Zhang et al., 1997), the duration of this cold weather is extraordinary. While the temperature was returning to the climatological level in late December, another cold surge occurred in early January and prolonged the cold weather for a week. As shown in Fig. 1b, the anomalous cold temperature averaged for the incipient stage of the cold period from 2 December 2005 to 10 January 2006 is found in most of East Asia, particularly in the Korean Peninsula and northeastern China.

The large-scale indices of the Siberian high and AO coherently reflect the temperature variation and enhancement in the EAWM circulation during this period (Fig. 1c). The correlation coefficients among these three variables for the analysis period are as follows: −0.89 for Siberian high vs. SAT, 0.62 for AO vs. SAT, and −0.68 for Siberian high vs. AO. All those correlation coefficients are significant at the 99% confidence level. It is interesting to note that the temporal relationship between the Siberian high and AO is not as linear as we expected. They are almost in phase in December, but are out-of-phase in January and February. However, we pay an attention on the signs of the Siberian high and AO to explain that cold surge occurs with the negative phase of AO and strengthening of the Siberian high. The Siberian high and AO indices apparently show an opposite sign for the analysis periods. This is in agreement with prior studies dealing with the Siberian high, AO, and SAT in East Asia (e.g., Gong et al., 2001; Wu and Wang, 2002; Jeong and Ho, 2005).

Figure 2 shows the horizontal distributions of the large-scale features during the 2005/06 winter. As a whole, the mean large-scale features during the 2005/06 winter represent the typical characteristics of a strong EAWM. Negative temperature anomalies (Fig. 2a), along with enhanced northerly winds (Fig. 2c), are found over East Asia, and a strong Siberian high (Lau and Lau, 1984; Boyle, 1986) is also apparent (Fig. 2e). As observed in Fig. 2a, strong cold

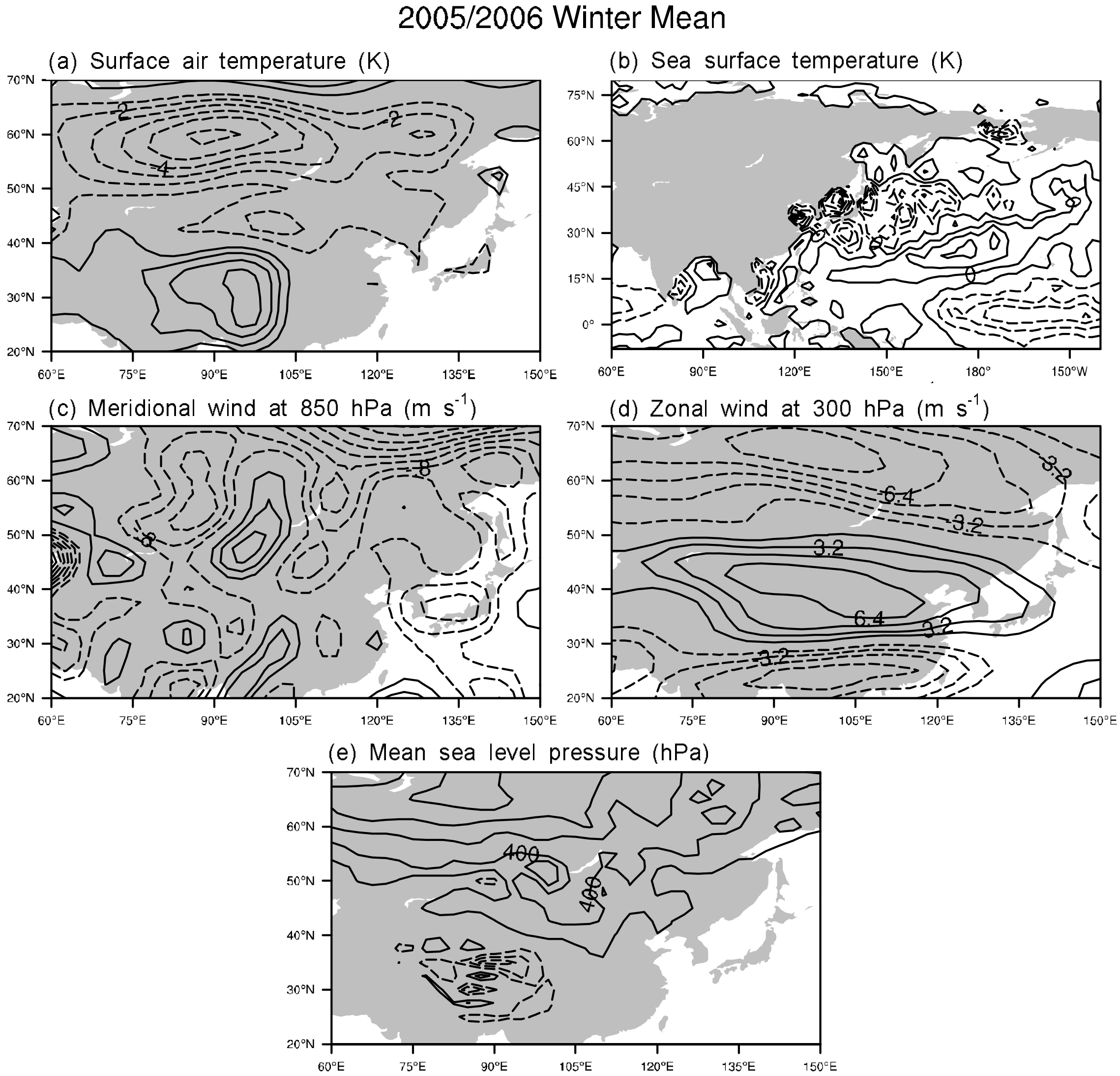

Fig. 2. 2005/06 winter (from December to February) mean anomalies of (a) temperature at 1000 hPa, (b) sea surface temperature, (c) meridional wind at 850 hPa, (d) zonal wind at 300 hPa, and (e) mean sea level pressure.

anomalies up to $-6°$C overwhelm the northern part of the Eurasian Continent and expand to northern China and Korea. These continental cold anomalies in East Asia seem to be associated with negative values in the SST anomaly over the northwestern Pacific (Fig. 2b). The lower-tropospheric northerly wind (Fig. 2c) seems to cause strong cold advection near the surface, and an upper-level zonal wind at 300 hPa (Fig. 2d) exhibits enhanced jet-stream intensity, which implies an increased meridional temperature gradient in East Asia.

While the seasonal mean features of 2005/06 are indicative of or very favorable for cold surge occurrences, this cannot solely explain the dynamical evolutions of the cold surges. In the following section, the distinctive intensification of the Siberian high and the subsequent evolution of two cold surges will be investigated in detail.

3.2 *Cold surge occurrence on 2 December, 2005: "Pacific origin" type*

Figure 3 presents the evolution of geopotential height anomalies at 50 hPa (Z'_{50}: left panels) and 300 hPa (Z'_{300}: middle panels) and the MSLP (right panels) from the sixth day prior to the occurrence of the cold surge (hereafter referred to as "day -6") to the second day following the occurrence (hereafter referred to as "day +2") on 2 December 2005. On day -6, strong positive Z'_{50} are observed over the Arctic near the Beaufort Sea and negative Z'_{50} occur in northeast-

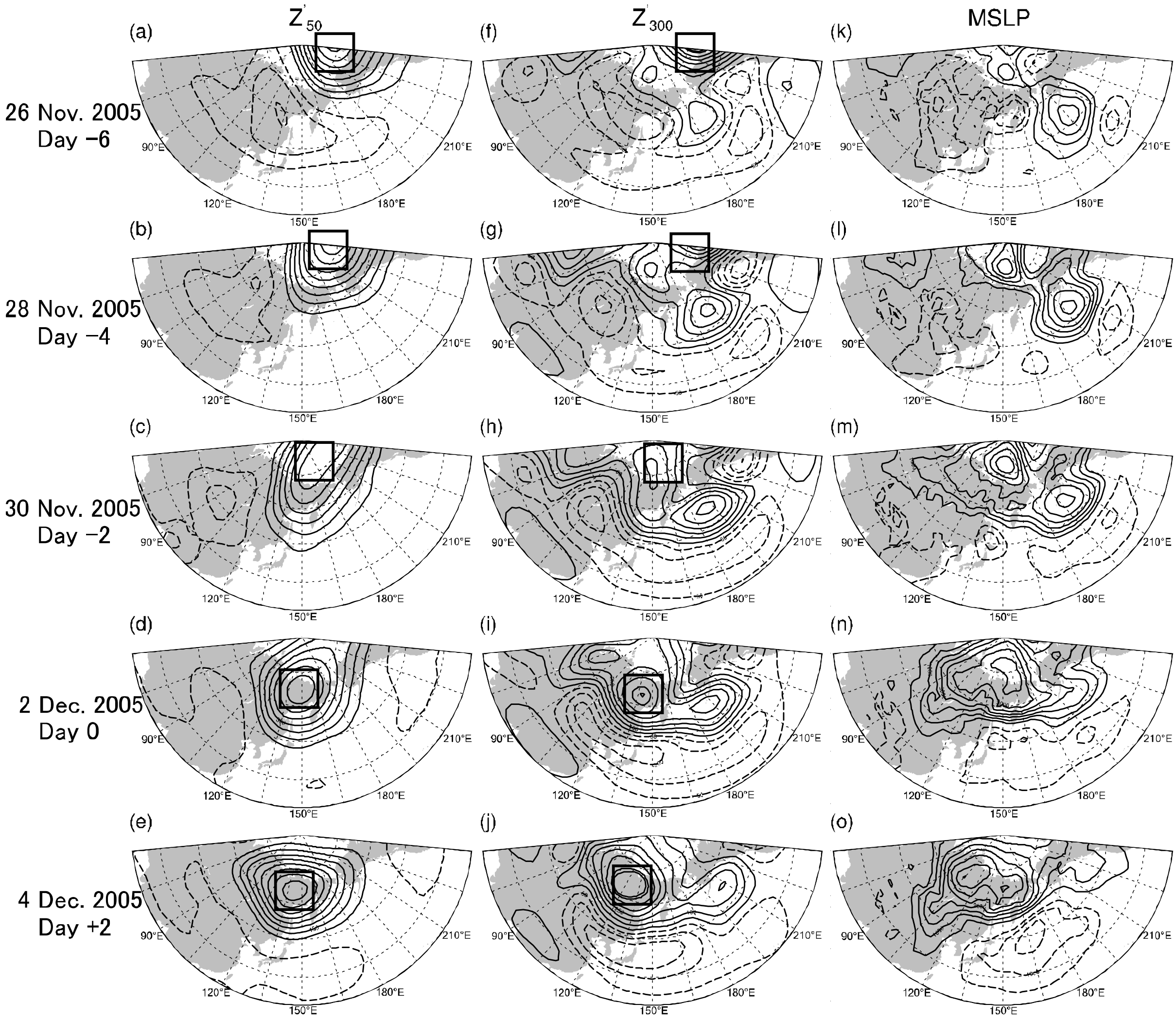

Fig. 3. Geopotential height anomaly at (a)–(e) 50 hPa (contoured every 75 m) and (f)–(j) 300 hPa (contoured every 75 m), and (k)–(o) mean sea level pressure anomaly (contoured every 5 hPa) during day −6 to day +2 relative to the cold surge occurrence on 2 December 2005. Solid and dashed lines represent positive and negative values, respectively. Boxes indicate the centers of positive geopotential height anomaly at 50 hPa and 300 hPa related to retrogressing anomaly.

ern Eurasia (Fig. 3a). From day −6 to day +2, for 8 consecutive days (Figs. 3a–3e), the positive Z'_{50} propagate southwestward to northeastern Eurasia. These large-scale anticyclonic anomalies in the lower stratosphere are closely related to the upper-tropospheric geopotential height Z'_{300}; strong positive Z'_{300} are observed below the positive Z'_{50} (Figs. 3f–3j). The negative Z'_{50} over northeastern Eurasia are also associated with the entire tropospheric circulation, but considering their smaller magnitude to Z'_{300}, they seem to be affected by a stronger signal in the upper-troposphere. It is noteworthy that the barotropic linkage of the anticyclonic Z'_{50} and Z'_{300} are reminiscent of upper-level blocking (Rex, 1950; Takaya and Nakamura, 2005a). Furthermore, the southwestward propagation of strong positive Z'_{50} and Z'_{300} initiated from the polar region is highly suggestive of a slowly retrogressing anomaly pattern in northern high latitudes (Branstator, 1987; Kushnir, 1987; Lau and Nath, 1999). Takaya and Nakamura (2005a) suggested that this pattern is related to a strong feedback forcing from the Pacific storm track. The large positive values of Z'_{300} from the polar region provide the positive-negative dipole pattern in the meridional direction, i.e., from northwestern Pacific to East Asia. Coinciding with the dipole pattern, the southwestward extension of the Siberian high associated with this upper-tropospheric circulation (from the polar region near northeastern Eurasia to East Asia) is clearly shown in Figs. 3k–3o.

The modulation of the amplification of the Siberian

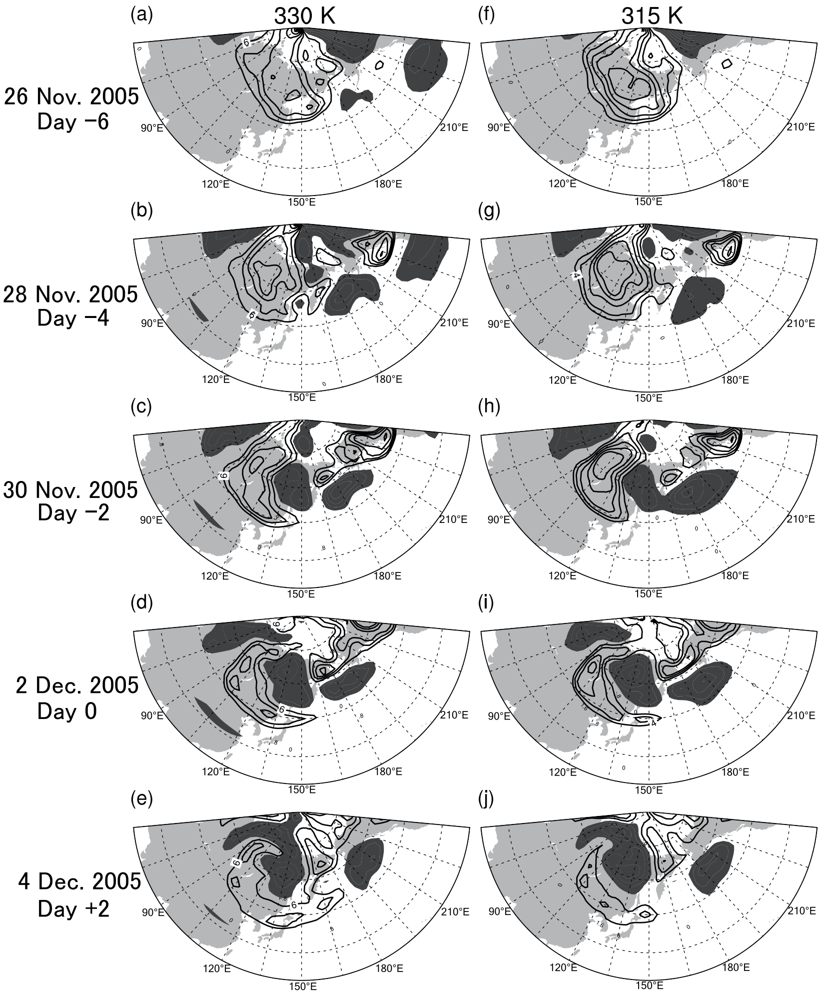

Fig. 4. Total IPV (contour) and its anomaly (shaded) at isentropic surfaces of (a)–(e) 330 K and (f)–(j) 315 K during day −6 to day +2 relative to the cold surge occurrence on 2 December 2005. Total IPV values are contoured every 0.5 potential vorticity unit (PVU; 1 PVU ∼10^6 m^2 s^{-1} K kg^{-1}) from 6 PVU (at 330 K) and every 0.5 PVU from 4 PVU (at 315 K). Negative (⩽ −1 PVU) values of IPV anomaly are shaded by grey.

high and the subsequent cold surge occurrence by such upper-level blocking can be observed in the corresponding evolution of the IPV and its anomalies at 330 K and 315 K (Fig. 4), which roughly correspond to the upper and middle troposphere. With regard to the typical polar vortex in the northern hemispheric winter, on days −6 and −4 (Figs. 4a–4b and 4f–4g, respectively) the high IPV centered over the Sea of Okhotsk is widely spread over northeastern Eurasia, and the negative IPV anomalies related to the upper-level blocking lie over the Bering Sea during the same period. From day −2 to day +2 (Figs. 4c–4e and 4h–4j), the negative IPV anomalies penetrate the high-IPV (i.e., polar vortex) region. Meanwhile, the high IPV is distorted and further elongated toward the Far East, which is located south of the negative IPV anomalies. The high IPV can bring the strengthening of the East Asian jet stream (i.e., an increase in the south-north temperature gradients), which is one of favorable large-scale conditions prior to cold surge occurrence in company with the amplification of the Siberian high and the strong cold advection.

To reveal the vertical coupling between the upper-level IPV and lower-level circulation, we examine the evolution of vertical cross-section of geopotential height, potential vorticity, and potential temperature anomalies averaged over latitudes of the core of positive-negative dipole pattern in Z'_{300} (Fig. 5). Figures 5a–5e represent the strong barotropic structure of the upper-level blocking and its slowly southward propagation in the entire troposphere, as is stated above. A negative PV anomaly is found in 60°N at 300 hPa,

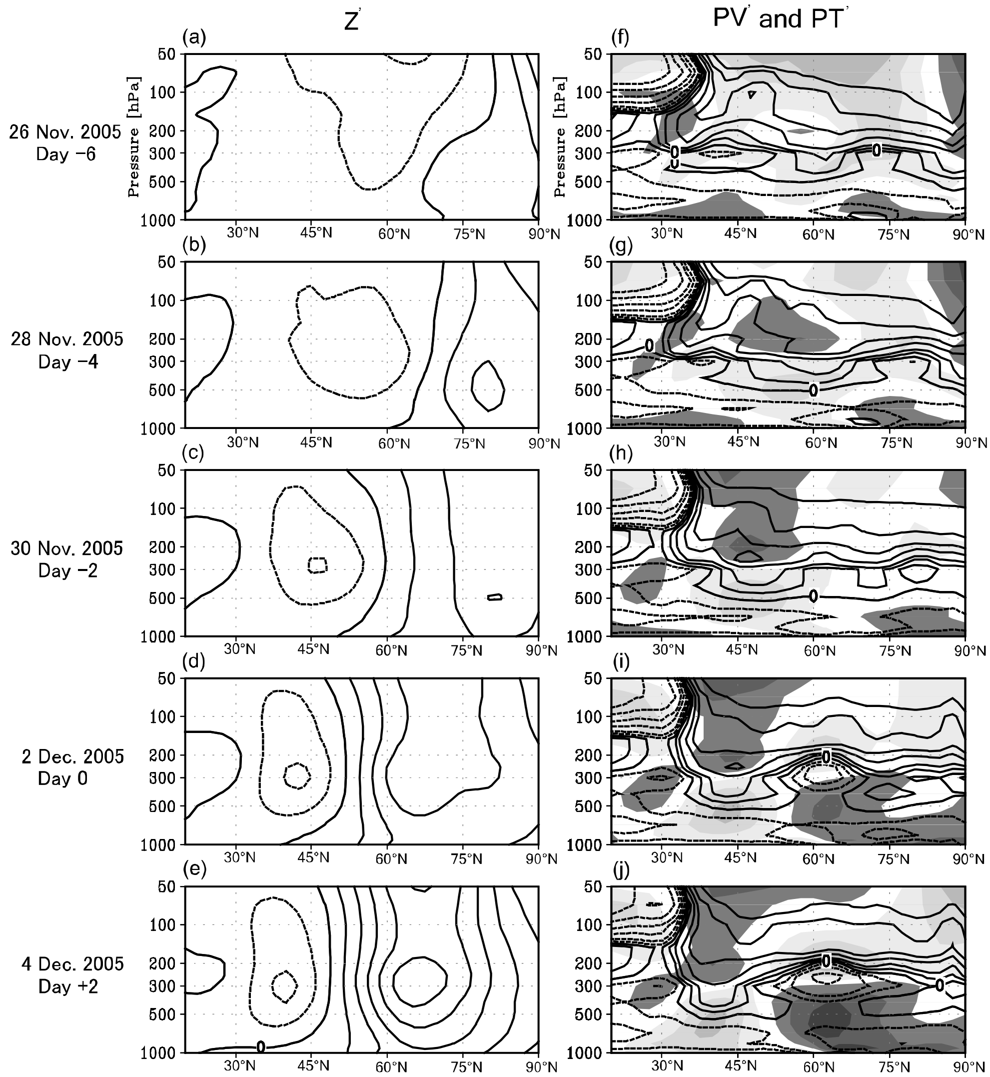

Fig. 5. Latitude-vertical cross-section of (a)–(e) geopotential height anomaly (contoured every 100 m), (f)–(j) potential vorticity anomaly (contour; contoured every 0.5 PVU) and potential temperature anomaly (shaded; positive and negative values are shown using dark- and light-grey shades, respectively) averaged over 110°E to 125°E during day −6 to day +2 relative to the cold surge occurrence on 2 December 2005. Solid and dashed lines represent positive and negative values, respectively.

and there is a tropospheric warming under the negative PV′ region (Figs. 5i and 5j) which points out the bending of the isentropic surface to the lower level. Below a positive PV anomaly in 40°N at the tropopause, the opposite situation (i.e., a cooling signal in the troposphere) is observed. As suggested by Hoskins et al. (1985), the isentropic surface tends to bend toward the positive PV′, which means the warming (cooling) of the region below negative (positive) PV′. In general, the present results are in agreement with their suggestions. It is also noted that regions of the upper-level negative (positive) PV′ and the tropospheric warming (cooling) coincide with positive (negative) Z' in the troposphere (Figs. 5a–5e), which is a consequence of geostrophic and hydrostatic adjustments processes. The strong positive Z' over the area north of 45°N induces a surface anticyclonic anomaly, which intrudes into East Asia under the upper-level negative Z' and further leads the amplification of the surface high (i.e., the Siberian high). The strong barotropic signature indicating positive Z' (Figs. 5a–5e) supports such an influence of the upper-level PV′ and the tropospheric PT' on the surface.

So far, the circulation related to the first cold surge was examined. We now investigate the thermal energetics using the thermodynamic energy equation for

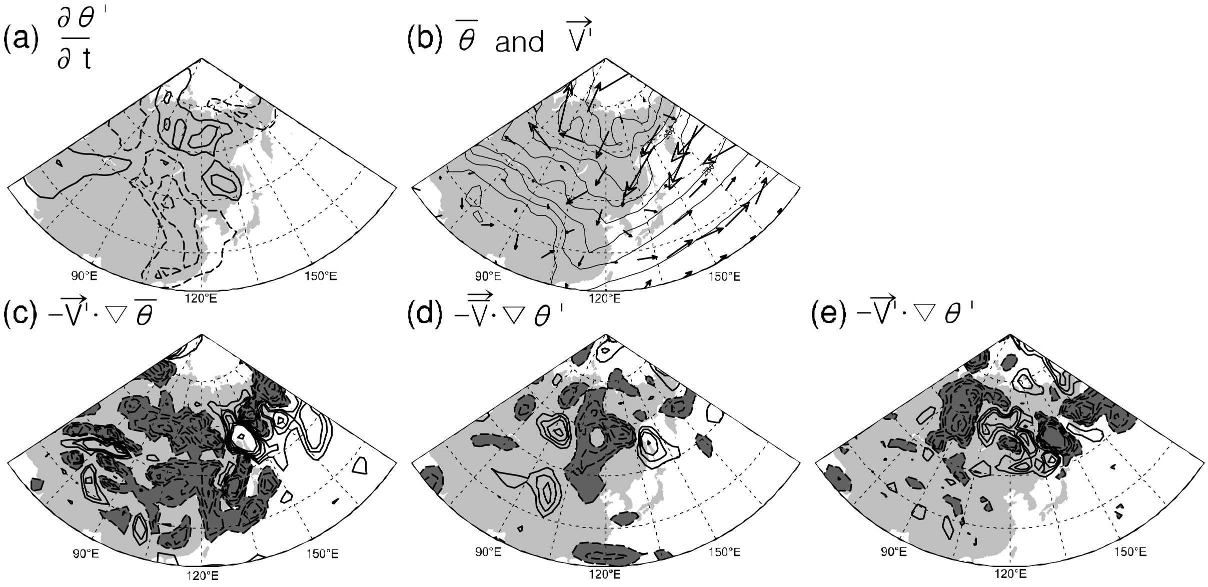

Fig. 6. (a) Tendency of potential temperature anomaly (contour lines are ±1, ±2, ±3, ±5, ±7, ±10, ±30 K d^{-1}, and negative values are contoured by dashed), (b) climatological potential temperature (contour; interval is 7 K from 245 K to 294 K) and horizontal wind (vector), (c) the advection of climatological potential temperature by anomalous wind, (d) the advection of anomalous potential temperature by climatological wind, and (e) the advection of anomalous potential temperature by anomalous wind [in (c)–(e), contour-line values are identical to those in (a) and negative values are contoured by dashed lines and shown using grey shades] corresponding to $\sigma_{0.995}$, which are averaged for days ±2 relative to the cold surge occurrence on 2 December 2005.

$\sigma_{0.995}$. Takaya and Nakamura (2005a) suggested that the low-level cold advection induced by upper-level factors along with the aid of strong vertical coupling is essential for the further amplification of surface anticyclones. Figure 6 illustrates the potential temperature tendency (Fig. 6a), the climatological potential temperature and the anomalous wind (Fig. 6b), and their breakdown (Figs. 6c–6e) by averaging the left-hand-side term and the terms (a–c) on the right-hand side in Eq. (3) for the period 31 November to 4 December (days ±2 relative to the cold surge occurrence). Negative tendencies of the potential temperature anomalies, i.e., the temperature drop, over East Asia are evident during this period (Fig. 6a). The spatial pattern of the negative tendencies can be mostly attributed to the advection of the climatological potential temperature by the anomalous wind ($-\boldsymbol{V}' \cdot \nabla\bar{\theta}$); the pattern illustrates the predominance of the terms indicating the total change over East Asia (Fig. 6c): the advection of the anomalous potential temperature by the climatological wind ($-\overline{\boldsymbol{V}} \cdot \nabla\theta'$, Fig. 6d) and anomalous wind ($-\boldsymbol{V} \cdot \nabla\theta'$, Fig. 6e). As shown in Fig. 6b, from the surface anticyclone in eastern Russia, the low-level northerlies or northeasterlies cross the region of steep meridional temperature gradient and result in a strong negative tendency in East Asia.

Summarizing the above description, the first cold surge occurred with the southward expansion of the Siberian high and originated from upper-level blocking, while the related anomalous wind with a steep climatological temperature gradient caused very strong cold advection. Additionally, as can be seen in Fig. 1a, the cold surge occurrence overlapped with the decreasing temperature trend of the seasonal cycle at the beginning of winter, and it may have reinforced the temperature tendency that lasted for more than two weeks.

3.3 *Cold surge occurrence on 2 January 2006: "Wave-train" (Atlantic origin) type*

Now we discuss the second cold surge that occurred on 2 January, which prolonged the extremely cold period for approximately one week, as shown in Fig. 1a. The second cold surge appears to have originated from the other typical source, the "wave-train" (Atlantic origin), suggested by Takaya and Nakamura (2005a). For the period from day −6 to day +2 with respect to January 2, Z'_{50}, Z'_{300}, and MSLP$'$ are presented in Fig. 7. The amplification and expansion of the Siberian high are apparent, but the evolution patterns are quite different from those of the first cold surge occurrence. Negative Z'_{50} values are located over the Bering Sea on day −6 (Fig. 7a), and they propagate to eastern Siberia from day −6 to day 0 (Figs. 7a–

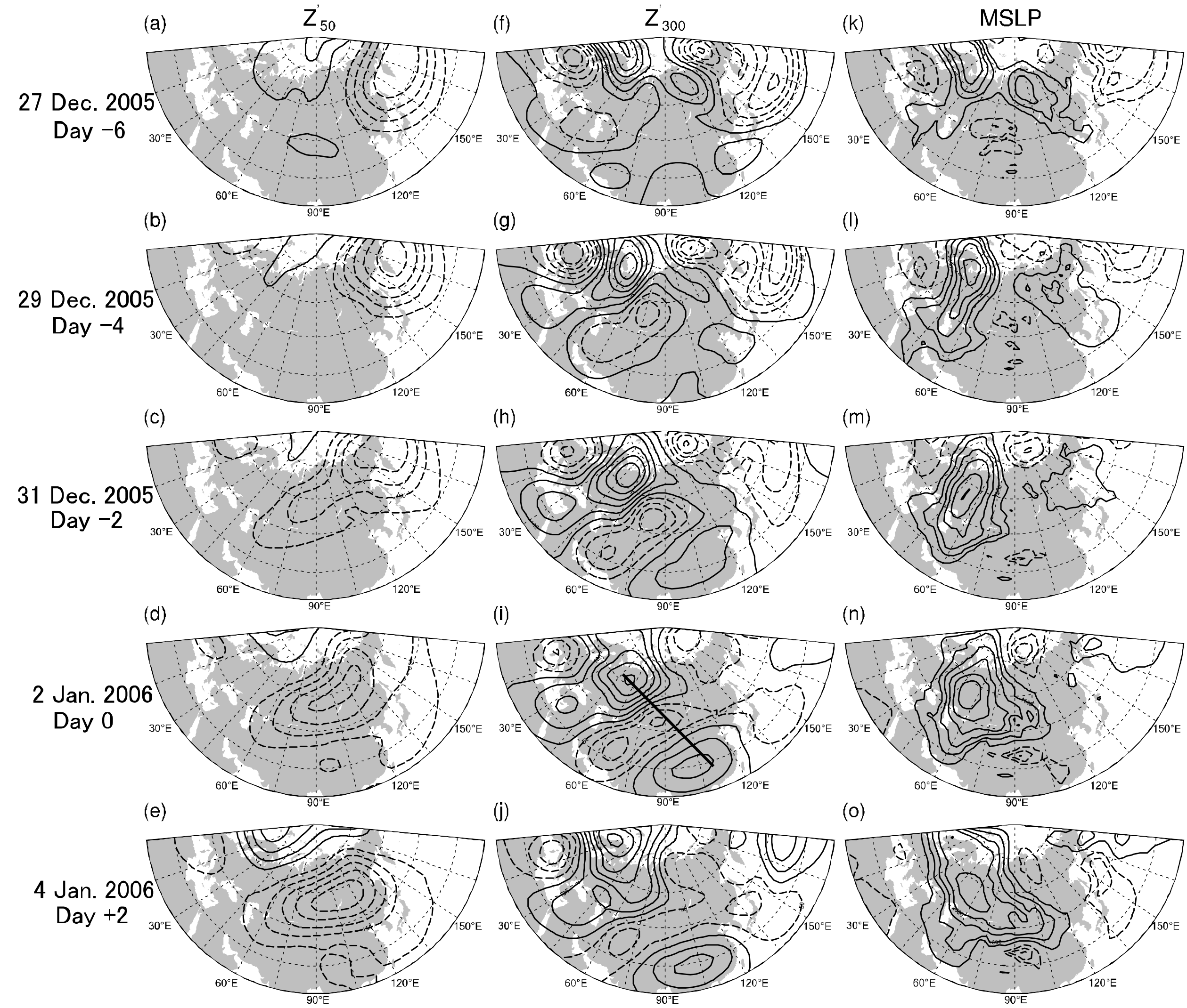

Fig. 7. Same as Fig. 3 except that the figure is for the cold surge occurrence on 2 January 2006.

7e) while positive Z'_{50} values are amplified around the Arctic Sea (70°–80°N, 0°–30°E). In the upper troposphere (300 hPa), the negative and positive Z' are alternately aligned in the northwest-southeast direction from Western Europe to East Asia from day −6 to day +2 (Figs. 7f–7j). Along the path of wave-train type disturbances at upper-levels, the Siberian high is amplified near the Ural Mountains, and it expands toward East Asia at the surface (Figs. 7k–7o).

In order to further investigate the mechanism for the second cold surge occurrence initiated by the upper-level wave-train and its following processes, a vertical cross-section of Z' and PT$'$ along the path of wave-train [from (70°N, 30°E) to (20°N, 120°E), indicated by solid line in Fig. 7i] is presented in Fig. 8. During day −6 to day −4, positive Z' over 30°–50°E and negative Z' over 60°–80°E form the wave-train type disturbance exhibiting a barotropic structure. Propagating southeastward, the wave-train becomes more baroclinic with westward tilting of Z' in the vertical direction (Figs. 8c–8e). At the same time, PT' tilts slightly eastward with height and has a phase difference with Z' (Figs. 8h–8j). As a whole, the baroclinic system formed by the westward tilting of Z' may be enhanced by differential temperature advection with respect to height, which implies the eastward tilting of temperature anomalies and a phase difference with Z'. Thus, Fig. 8 shows typical characteristics of a developing baroclinic wave, which are essentially different from the barotropic structure in the first cold surge event. For a growth of the baroclinic wave, strong positive Z' near the surface level intrudes into East Asia under the negative Z' in the mid- and upper-troposphere. Those represent the southeastward propagation of the Siberian high (Figs. 8c–8e). Those upper-level disturbances and following processes—

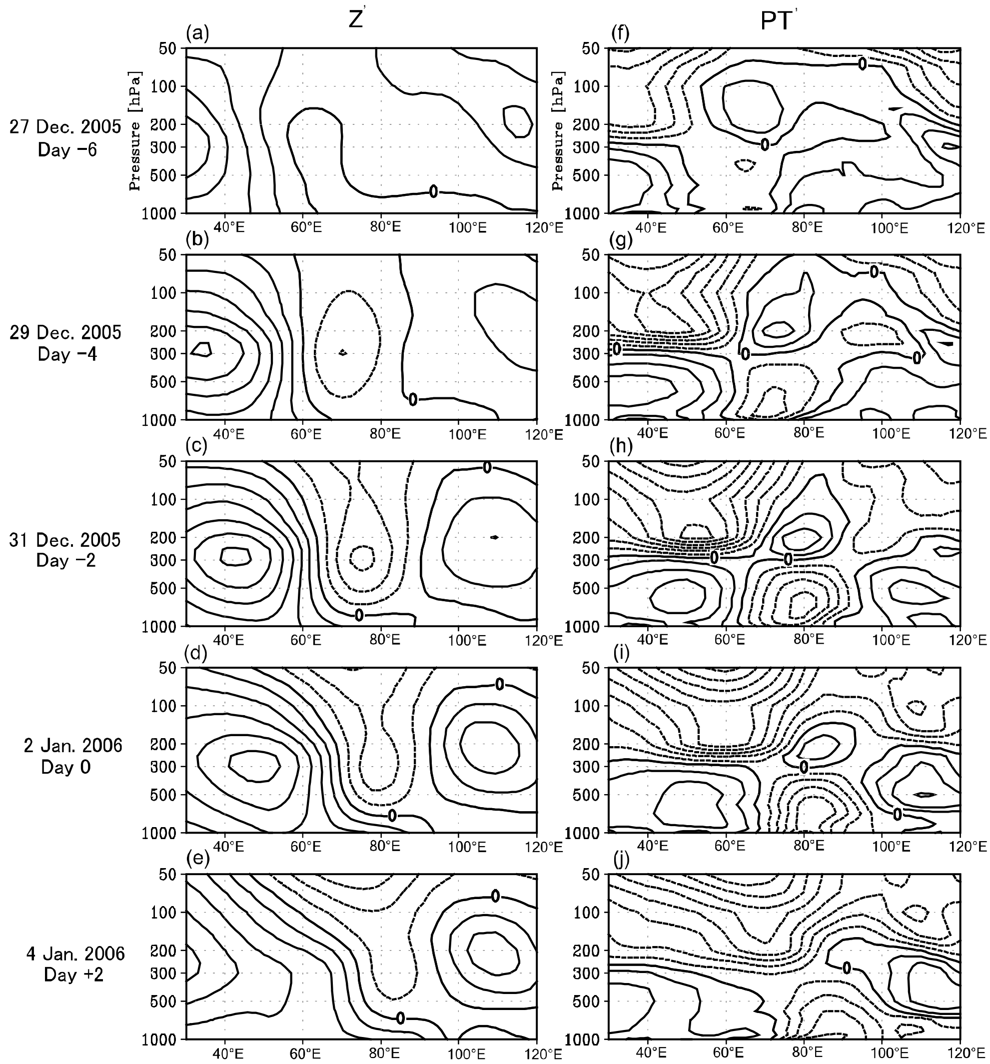

Fig. 8. Vertical cross-section of (a)–(e) geopotential height anomaly (contoured every 75 m), (f)–(j) potential temperature anomaly (contoured every 3 K) along the thick line in Fig. 7i [from (70°N, 30°E) to (20°N, 120°E)] during day −6 to day +2 relative to the cold surge occurrence on 2 January 2006. Solid and dashed lines represent positive and negative values, respectively.

enhanced baroclinity and southeastward amplification of the Siberian high—would be typical precursory signals for the occurrence of cold surges, as suggested by previous studies (Zhang et al., 1997; Chen, 2002; Jeong et al., 2006). According to prior studies, the typical processes to lead to the occurrence of cold surge are summarized as follows. The upper-level wave-train (trough-ridge) deepens the tropospheric trough near the East Asian coast as it propagates southeastward, which induces the tropospheric northwesterly wind over East Asia with cold air from the main reservoir of the continent. The northwesterly wind forms an anticyclonic circulation over the Siberian region. At the same time, the expansion of the Siberian high to East Asia along the upper-level wave-train accelerates the northwesterly wind at the east edge of the high. The interaction between the amplification of the Siberian high and the northwesterly wind brings out a strong cold advection to East Asia and leads to the occurrence of cold surge (Lau and Lau, 1984; Zhang et al., 1997; Chen, 2002).

Takaya and Nakamura (2005b) suggested that cold advection and surface cold anomalies are important in increasing the strong baroclinic growth in a cold surge outbreak of the wave-train type. So, similar to the analysis of the first cold surge, the composite maps of the thermal advection terms and tendency averaged for five days from day −2 to day +2 relative to the

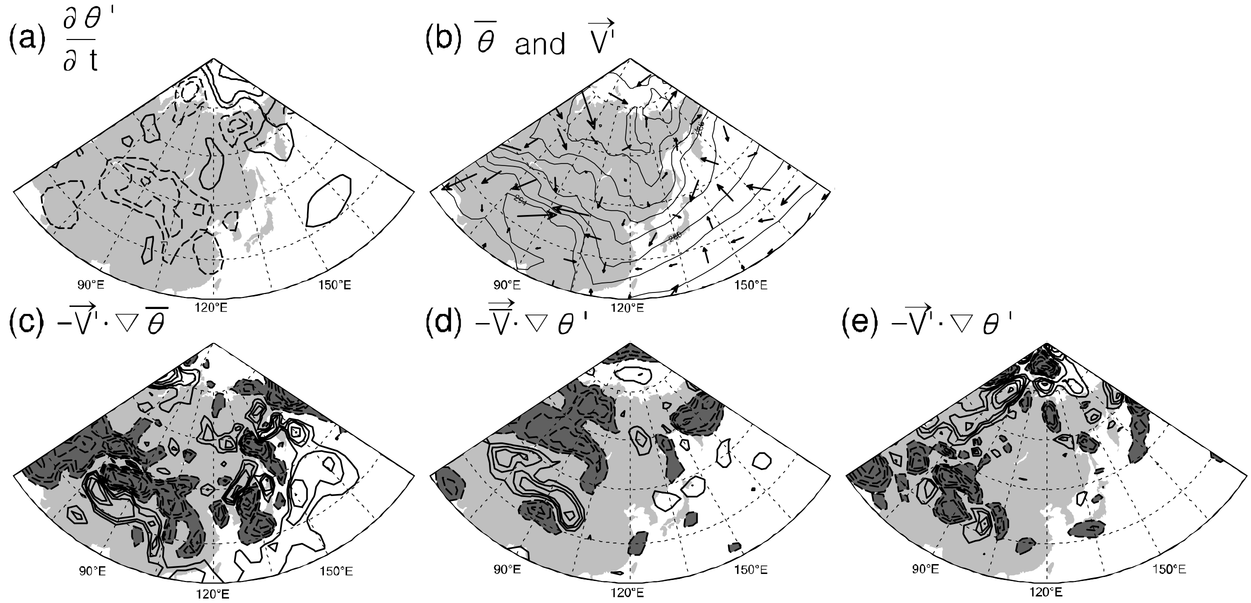

Fig. 9. Same as Fig. 7 except that the figure is for the cold surge occurrence on 2 January 2006.

second cold surge occurrence are displayed in Fig. 9. Strong cooling is evident from southern Siberia to East Asia along the northern flank of the Tibetan Plateau (Fig. 9a). In Fig. 9b, we can observe that the low-level northerlies cross the steep meridional temperature gradient in these regions. Similar to the case of the first cold surge, the negative tendencies of the potential temperature anomalies over East Asia are mostly attributed to the advection of the climatological potential temperature by the anomalous wind term ($-\boldsymbol{V} \cdot \nabla\theta'$, Fig. 9c), which is considerably larger than the other two terms (Figs. 9d and 9e; $-\bar{\boldsymbol{V}} \cdot \nabla\theta'$, $-\boldsymbol{V} \cdot \nabla\theta'$). Comparing Figs. 8m–8o and 10a, the surface strong cold advection seems to lead to the expansion of the Siberian high along the upper-level wave-train. The induced cold anomalies interact with the upper-level system, which in turn can act to amplify the baroclinic system. According to the PV inversion analysis of Takaya and Nakamura (2005b), the surface cold anomalies induce anticyclonic flow at upper-levels over the Eurasian continent, which leads to positive and negative anomalous vorticity advections on the west and east edges of the flow, respectively. These vorticity advections intensify the upper-level anticyclonic Z' over the Siberian region and cyclonic Z' over the Far East, which implies the amplification of the upper-level wave-train. As the surface cold anomalies gradually extend southeastward along the expansion of the Siberian high, it reinforces the baroclinic wave-train.

As a result, the upper-level baroclinic wave-train led to the amplification and southeastward expansion of the Siberian high by inducing strong cold advection, which resulted in the cold surge occurrence on 2 January.

4. Summary and discussion

The present study suggests the importance of the upper-level circulation and its modulating effect in amplifying the Siberian high to induce the two cold surges in East Asia during the 2005/06 winter. It is shown that the cold surges occurred due to two distinctive types of upper-level atmospheric circulation, i.e., the "Pacific origin" and "wave-train" (Atlantic origin) types. These two upper-level circulations evoked the cold weather sustained for about one month early in the 2005/06 winter over East Asia through two cold surge occurrences. We summarized the results in the following.

As for the first cold surge, retrogression of the upper-level blocking from the polar region to northeastern Eurasia brought the amplification of the Siberian high and the strengthening of the jet stream, which give rise to a strong cold advection through anomalous northerly wind and an increase in meridional temperature gradient. These conditions are overlapped with a decreasing trend of the seasonal cycle at the beginning of winter, and it reinforces the cold advection. The cold weather initiated by the first cold surges was sustained by the upper-level blocking which lasted for about three weeks over East Asia, namely the northeastern Pacific region. The meridional positive-negative dipole pattern, which is responsible for the initiation of the first cold surge, was sustained for about three weeks (figure not shown). As such, the lasting blocking might induce anomalous northerly flow, a continuous supply of the cold air to East Asia from northern latitudes. Also, as the climatological cold-core Siberian high and surface northwesterlies of EAWM are getting stronger from November, the climatological cycle of SAT exhibits a steep decreasing trend during the cold weather period and about a 5°C decrease seems to result from the seasonal cycle (Fig. 1a). Thus the combined effect by lasting blocking and the seasonal march of the EAWM circulation might lead to extraordinary cold weather for a long period. After the blocking vanished, as for the second cold surge, the growing baroclinic wave-type disturbances in the upper-level, propagating across the Eurasian continent, reinforce the intensification of the Siberian high with a strong cold advection across the meridional temperature gradient. Consequently, the cold weather is prolonged to early January, 2006.

By analyzing the two distinct cold surge cases, the present study suggests the increased practical use of the upper-level atmospheric circulation in predicting cold surge occurrences. However, how the upper-level blocking is formed and maintained for more than three weeks is not clearly resolved, though the occurrence and maintenance of the blocking are involved such as internal dynamical processes in the extratropics (Dole and Gordon, 1983), the ENSO-related Pacific-North America (PNA) pattern (Renwick and Wallace, 1996), the tropical SST anomaly (Lee and Jhun, 2006), and the Eurasian snow cover (Wang, 2006). Also, the source of the wave-train across the Eurasian continent still remains unknown. They are beyond the scope of the present study. Therefore, an analysis of long-term data and a numerical modeling approach using the PV inversion technique (Davis and Emanual, 1991; Black, 2002) will be performed in the future in-depth researches. This may not only provide a better understanding of the dynamical mechanism for forecasting cold surges, but may also be more helpful for solving problems that remain.

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