The 2009 Summer Low Temperature in Northeast China and Its Association with Prophase Changes of the Air-Sea System

SHEN Baizhu[1,2](沈柏竹), LIU Shi[1,2](刘 实), LIAN Yi[1,2]*(廉 毅), FENG Guolin[3](封国林),

LI Shangfeng[1,2](李尚锋), and GONG Zhiqiang[3](龚志强)

1 *Laboratory of Research for Middle-High Latitude Circulation and East Asian Monsoon, Changchun* 130062

2 *Institute of Jilin Province Meteorological Science, Changchun* 130062

3 *National Climate Center，Beijing* 100081

(Received October 12, 2011)

ABSTRACT

Under the background of global warming, summer (JJA) low temperature events in Northeast China had not occurred for about 15 yr since 1994, but one such event took place in 2009. By using the NCEP/NCAR reanalysis data, the 100-yr station temperature data at Harbin and Changchun, and the Hadley Center sea surface temperature (SST) data, this paper intends to reveal the cause, circulation background, and influencing factors of this event. Analysis of both horizontal and vertical circulations of a low-value system over Northeast China in summer 2009 during the low temperature event shows that anomalous activities of the Northeast China cold vortex (NECV) played the most direct role. A decadal cooling trend of –0.8°C (10 yr)$^{-1}$ over 1999–2008 at Changchun and Harbin was found, which is obviously out-of-phase with the linear warming trend (0.2°C (10 yr)$^{-1}$) over 1961–2000 for Northeast China in response to the global warming. The previous winter North Pacific polar vortex (NPPV) area index, significantly positively related to the observed summer temperatures of Harbin and Changchun, was also in a significantly declining tendency. These provide favorable decadal backgrounds for the 2009 low temperature event. Different from the average anomaly field of 500-hPa height for summer 1994–2008 in Northeast China, in the summer of 2009, the Arctic Oscillation (AO) showed a strong negative phase distribution, and significant negative height anomalies dominated Northeast Asia, Aleutian Islands, and North Atlantic. Furthermore, the negative phase of North Pacific Oscillation (NPO) in the winter of 2008 was obviously strong, and it maintained in the spring of 2009. Meanwhile, the SSTA in the equatorial eastern-central Pacific Ocean in the winter of 2008 showed a La Niña phase, but the strength of the La Niña weakened obviously in the spring of 2009. The abnormally strong activities of NECV in June and July of 2009 were related to the disturbances of stationary waves that replaced the original ultra-long waves over the North Pacific region in April and May 2009. The singular value decomposition (SVD) and harmonic analysis results suggest that the anomalous phase of NPO is an important precursor for summer temperature variations over Northeast China, and also a stable planetary-scale component that can be extracted from the atmospheric circulation in addition to the chaotic components on the synoptic scale.

Key words: global warming, summer low temperature in Northeast China, decadal variability, Northeast China cold vortex, polar vortex, North Pacific Oscillation

Citation: Shen Baizhu, Liu Shi, Lian Yi, et al., 2012: The 2009 summer low temperature in Northeast China and its association with prophase changes of the air-sea system. *Acta Meteor. Sinica*, **26**(4), 438–453, doi: 10.1007/s13351-012-0404-9.

1. Introduction

Low temperature cold injury events frequently occur in summer during the crop growth period (May–September) in Northeast China from the 1950s to 1970s. Different from low temperature/freezing damage, low temperature/cold injury usually refers to crop injury resulted from the low temperature above 0°C

Supported by the National Natural Science Foundation of China (41175083, 41275096, and 40705036), National Science and Technology Support Program of China (2009BAC51B04 and 2007BAC29B01), and China Meteorological Administration Special Public Welfare Research Fund (GYHY 20106020 and 201106016).

*Corresponding author: lianyi1103@sina.com.

(Chinese version published in Vol. 69, No. 2, 320–333, 2011)

(sometimes even about 20°C) in its growth phase (Zhang, 1990; Wang, 1995). Low temperature/cold injury events in the summers of 1969, 1971, 1972, 1976, and 1979 resulted in about 20% reduction of the annual total grain output of Jilin Province, especially the rice as high as 30%–50% (the General Office of the People's Government of Jilin Province, 2002). This has been attracted much attention by the Chinese researchers, and some investigations have been performed since the end of the 1970s. It was found that the Northeast China summer low temperature (NESLT) events are correlated with the negative temperature anomaly in the mid-high latitudes of Northern Hemisphere (excluding the area north of 60°N), and they exhibit planetary-scale characteristics (Jilin Provincial Observatory, 1980; Zhang et al., 1982, 1983). Temperature changes at Harbin in 1881–1983 showed distinctive phases (Wang, 1995). During the cold phase of NESLT, the occurrence of El Niño adds a negative effect on the temperature, i.e., making it much lower than normal (Zhang, 1990). Occurrences of cool or hot summer in Northeast China were closely related to major large-scale circulation patterns in the Northern Hemisphere (Northeast China Summer Low Temperature Collaboration Team, 1979; Jilin Provincial Meteorological Observatory, 1980). Typical case analysis by Fu (1980) concluded that when the snow cover in the Northern Hemisphere and the sea ice in the Atlantic Ocean increase in pervious winter and spring, the summer temperature in Northeast China would be lower than normal. Zhang et al. (1985) and Liu (1986) investigated the association between NESLT and monthly variations of polar vortex. They defined the area and intensity indices of polar vortex, which reflect the interaction between polar vortex and mid-latitude circulation, and found that the polar vortex area index in the domain from Asia to the central Pacific was negatively correlated with temperature in Northeast China and most areas of China and the polar vortex intensity index was also negatively correlated with temperature in Northeast China.

Chinese researchers have conducted many studies to reveal the prophase influential signals of the air-sea system related to summer climate in Northeast China. Much attention has been paid to atmospheric semi-permanent activity centers that bear a barotropic structure with seasonal changes (Chou, 1986, 2007). Liu et al. (2002, 2003) and Lian et al. (2007) showed that there was a remarkable teleconnection between the oscillations of both the Aleutian low and the North Pacific Oscillation (NPO) in the subtropical region south of the Aleutian islands and the summer Northeast China Cold Vortex (NECV) and precipitation over eastern China. The intensity of summer NECV was positively correlated with the Northern Hemisphere annular mode (NAM) in February (He et al., 2006). Some decadal characteristics of NESLT events have been found (International CLIVAR Project Office, 1997): from the 1950s to 1970s, cool summers in Northeast China frequently occurred corresponding to the El Niño events in this period; however, since the 1980s, the El Niño events were often accompanied by warm or less cool summers (Wang and Wu, 1997; Lian and An, 1998; Lian et al., 2002[①]; An et al., 1998; Zheng and Ni, 1999; Sun and Wang, 2006). This indicates that interannual changes of NESLT are constrained by the longer term (10 yr or more) climate changes (Ding et al., 2003; Ding, 2007). How the decadal variability of climate affects the interannual variability of NESLT needs further investigations. Some consistency between the interdecadal and interannual variations of rainy-season precipitation in North China has been reported (Lu, 2003).

Global climate has entered the warmest period since the 1990s (IPCC, 2007), and Northeast China is one of the regions that exhibit a remarkable regional warming in response to the global warming (National Assessment Report of Climate Change Editorial Committee, 2007). The frequency of cool summer has significantly reduced since the 1980s; in particular, no large-scale summer low temperature event happened in Northeast China from 1994 to 2008 (Chen et al., 2004; Yang et al., 2005). However, a significant summer low temperature event occurred in Jilin and Hei-

① Lian et al., 2001: A re-evaluation of the impact of El Niño events on temperature in China. APN Summary Meeting, 49, Macau, 5–7 February 2002.

longjiang provinces in 2009. This raises a question: Is it an accidental event in the current warm phase or an early signal for the bulk NESLT events similar to those during the 1950s–1970s? At present, the conclusion of continuous global warming based on climate model simulations under the various IPCC SERS scenarios was obtained without considering the impact of natural forcing (Zhao et al., 2005, 2008). As far as adaptation to the global warming is concerned, carrying out appropriate research on natural variability of temperature is helpful (Ye and Yan, 2008). Northeast China has concentrated thermophilic rice farming in higher latitudes such as Heilongjiang Province. If the climate in Northeast China enters a relatively cool phase, this would pose a major threat to the grain production there, as Northeast China is a major grain production base with annual total grain yield accounting for 1/6 of China's total grain output. It is necessary to perform a case study on the summer low temperature in 2009, and to promote the studies on the decadal variability of NESLTs.

This paper diagnoses the circulation characteristics during the summer low temperature event in 2009, aiming to reveal the relationship between early-stage changes of the air-sea system and the summer low temperature, and the decadal background favorable for the NESLTs. The present study also tries to identify planetary-scale stable atmospheric components, in addition to the synoptic-scale chaotic components (Chou, 1986, 1997; Feng et al., 2006; Ren and Xiang, 2010; Lin et al., 2010; Zhi et al., 2010). Based on multiple spatial/temporal-scale analysis, causes of the 2009 summer low temperature in Northeast China are to be revealed.

2. Data and methods

The data used in this paper include daily temperature observations at Changchun Station from 1909 to 2008 and at Harbin Station from 1881 to 2008, the reanalysis data of NCEP/NCAR from 1948 to 2009 and that of ECMWF from 1958 to 2002, and the SST data of Hadley Center from 1881 to 2005. The temporal filtering of long period ($\geqslant$ 9 yr; decadal-scale component) and short period (< 9 yr; interannual-scale component) was performed on the time series of the above data, and the correlations between the interannual and interdecadal frequency spectra were then computed.

Based on the standard deviation (σ) of observed temperature series for about 100 yr at Changchun and Harbin stations, an NESLT event is defined as follows: at any station in Northeast China, if $\overline{T}_{6-8} \leqslant -1.0\sigma$ (subscript 6–8 denotes June–August, same below), a severe cool summer (A event) occurs; if $-1.0\sigma < \overline{T}_{6-8} \leqslant -0.4\sigma$, a cool summer (B event) occurs; if $-0.4\sigma < \overline{T}_{6-8} \leqslant -0.3\sigma$, a normal summer occurs; if $0.3\sigma < \overline{T}_{6-8} \leqslant 0.8\sigma$, a warm summer (C event) occurs; while $\overline{T}_{6-8} > 0.8\sigma$ denotes a severe warm summer (D event).

The temperature analysis by Lian and An (1998) showed that Changchun and Harbin stations can be taken as stations representative of the regional climate of Northeast China.

Table 1 shows that the frequencies of A events (levels 1–3) and B events (level 4) in summer were 14% and 23% at Changchun and 15% and 20% at Harbin, respectively. Therefore, A events occur less frequently than B events.

Based on Table 1, four (three) years of 1969, 1971, 1972, and 1976 (1954, 1957, and 1993) were chosen as the A (B) event years for Northeast China (represented by Changchun and Harbin) and seven (four) years of 1952, 1955, 1982, 1988, 1994, 1997, and 2000 (1982, 1988, 1994, and 1997) as the typical summer high temperature years. Then, composite wind and temperature anomaly fields were plotted. The vertical velocity was calculated by following Ding (1989).

Table 1. Classification of summer average temperature based on the standard deviation (σ) of observed temperation at Changchun and Harbin in the period 1909–2008 and corresponding occurence percentages

Level	1	2	3	4	5	6	7	8	9
Threshold (σ)	$\leqslant$–2.0	(–2.0, –1.4]	(–1.4, –1.0]	(–1.0, –0.4]	(–0.4, 0.3]	(0.3, 0.8]	(0.8, 1.4]	(1.4, 2.2]	>2.2
Changchun (Freq, %)	2	2	10	23	28	18	8	6	3
Harbin (Freq, %)	2	5	8	20	29	18	9	6	3

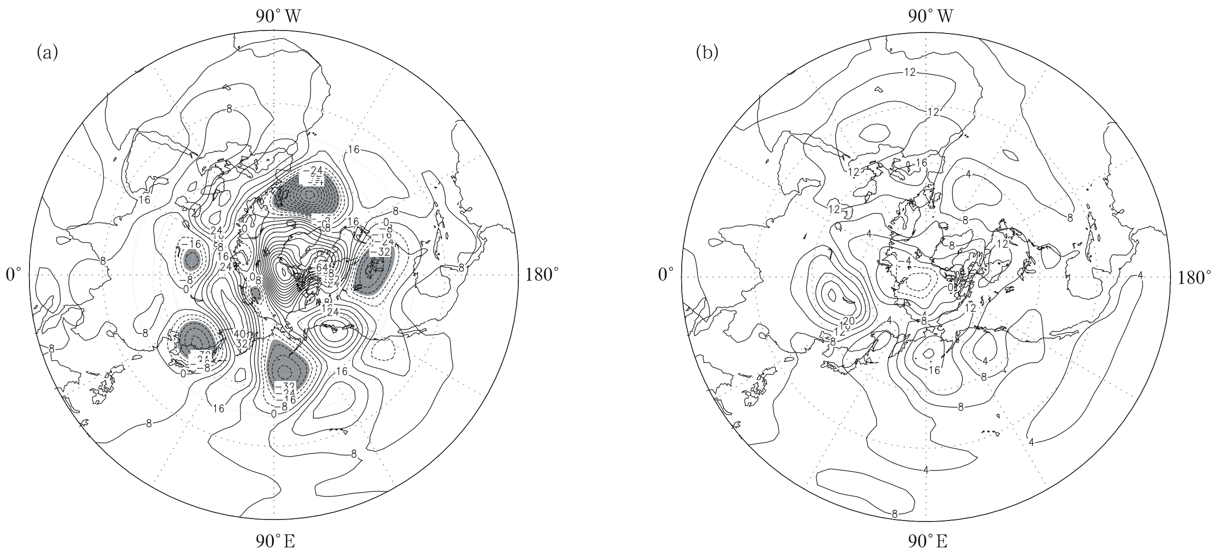

Fig. 1. Summer average 500-hPa geopotential height anomaly (gpm) patterns for (a) 2009 and (b) 1994–2008. Shadings denote areas with anomaly values less than –20. The contour interval is 4.

In this paper, we adopted the definitions of NECV and NPO given in Liu et al. (2003), and we followed Liu (1986) for computation of relevant polar vortex indices and selection of the domain of the Pacific polar vortex.

3. The 2009 NESLT case

3.1 500-hPa height anomaly in summer 2009

Figure 1a shows the summer (JJA) average 500-hPa height anomaly field for 2009. It can be seen that anomalous disturbances in the "two-trough-one-ridge" pattern appeared over Asia, i.e., there was a stable negative disturbance south of 55°N in Northeast Asia with its center in coastal Russia, and a positive anomaly region (a persistent active area of blocking highs) from the Lake Baikal to the Okhotsk Sea. The two anomaly regions with opposite signs formed a stable dipole pattern over Northeast Asia (including Northeast China), and sustained for two months. This was also to certain extent related to the stable activities of the low vortices in the semi-permanent active center over the Aleutian Islands.

Figure 1b displays summer average 500-hPa height anomaly field during 1994–2008. The Northern Hemispheric general circulation anomalies in Fig. 1a had signs almost opposite to those in Fig. 1b. In summer 2009, there was a strong positive anomaly over the polar region (indicating that AO was in a significant negative phase), and there were distinctive negative anomalies over Northeast Asia, Aleutian Islands, and North Atlantic.

3.2 Average temperature anomalies over China in summer 2009

Figure 2 shows summer average temperature anomalies over China in 2009. It can be seen that a wide range of low temperatures happened in Jilin Province and the central-eastern part of Heilongjiang Province, where negative temperature anomalies rang-

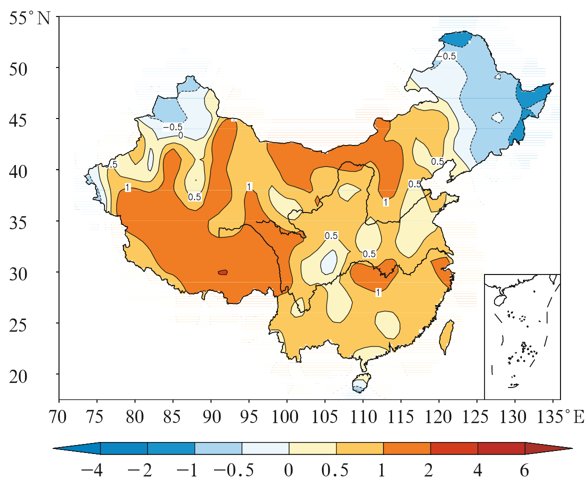

Fig. 2. Summer average temperature anomaly (°C) in 2009 over China.

ing from −0.5 to −1.0°C. Because the main body of the cold air mass resided in the eastern part of Jilin Province and the standard deviation of summer average temperature at Changchun was −0.49σ (<−0.4σ), the 2009 NESLT case reached the standard of a B event (cool summer).

4. Composite analysis

4.1 NECV activities

Table 2 shows the anomaly of NECV days in association with temperature deviations at Changchun and Harbin. The number of NECV days was more than normal in 8 yr out of the 11 A and B event years at Harbin and Changchun (the summer temperature of 2009 did not meet the threshold of A or B event at Harbin), normal in 1 yr, and slightly less in 2 yr (1976 and 1979). Even in 1976 and 1979, the NECV days for June only were also slightly more than normal (table omitted). In the 5 typical summer high temperature years of 1982, 1988, 1994, 1997, and 2000, the NECV days were 10–15 days less than normal (table omitted). Therefore, it is inferred that the positive anomaly of NECV days is correlated with NESLT, and vice versa, and the NECV is the system that directly influences the NESLT.

4.2 500-hPa height anomaly composites

Figures 3a and 3b show the summer 500-hPa height anomaly composites over 7 A events and summer high temperature years of Northeast China, respectively. It is seen that over the Asian mid-high latitudes, Aleutian Islands, and the northwest of North America, there were two hemispheric-scale wide-range negative and positive anomaly bands, with two low value centers over Northeast China and the Aleutian Islands, respectively. In the NESLT years, there were two summer low value activity centers in the Northern Hemisphere, one of them is the NECV center, where the active NECVs directly result in NESLT events. It is inferred that summer surface temperature over North Pacific under the active center of the Aleutian low might also be lower (Fig. 3a).

Figure 4 exhibits spatial distributions of the correlation coefficients of the summer average temperature

Table 2. Standard deviations of summer temperature at Changchun and Harbin and NECV days in NESLT years

	1957	1964	1969	1971	1972	1976	1979	1983	1986	1993	2009
Anomaly of NECV days	+29	+13	+21	+4	0	−3	−7	+6	+8	+7	+13
Changchun (σT)	−1.848	−1.390	−2.076	−1.172	−1.274	−1.527	−0.878	−1.155	−0.970	−0.865	−0.490
Harbin (σT)	−0.654	−1.109	−1.488	−1.298	−1.602	−0.578	−0.388	−1.867	−0.426	−1.222	−0.274

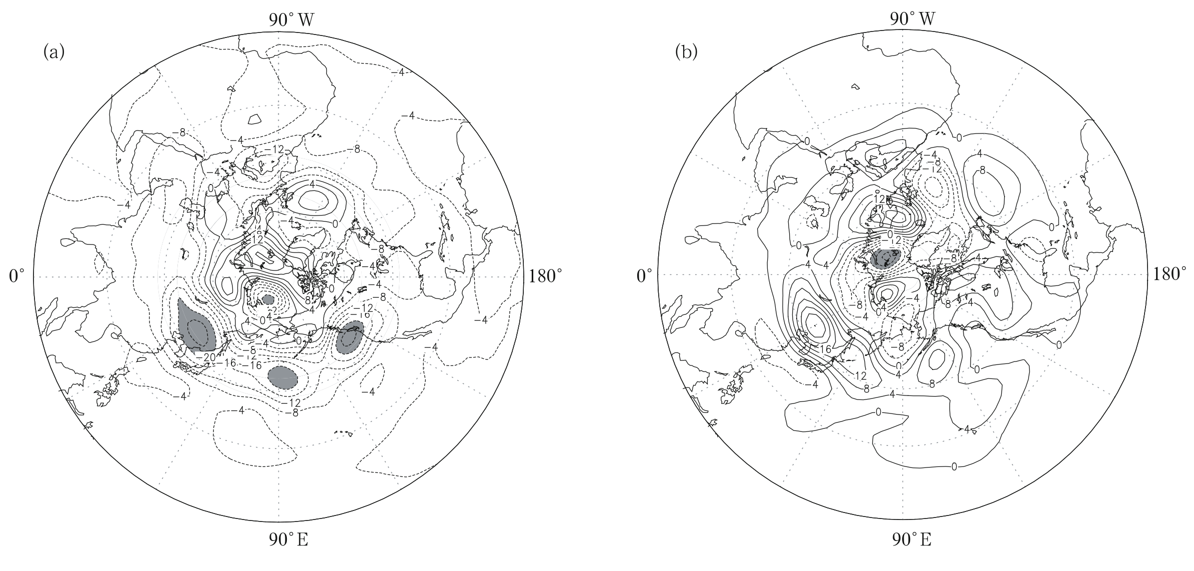

Fig. 3. Summer 500-hPa height anomaly (gpm) composites over (a) A event years and (b) typical summer high temperature years of Northeast China. Shadings illustrate the value of anomaly less than −20; contour interval is 4.

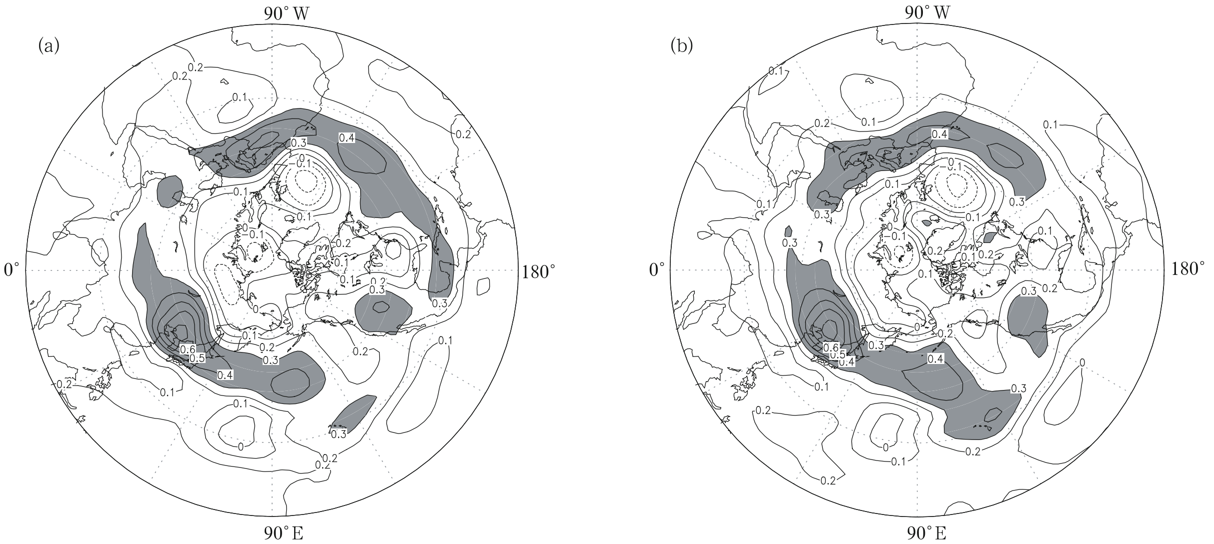

Fig. 4. Simultaneous dependence patterns of the summer temperature of (a) Changchun and (b) Harbin with North Hemispheric 500-hPa geopotential height. The significant correlations at the 0.05 confidence level are shaded; contour interval is 0.1.

at Changchun and Harbin with Northern Hemispheric summer 500-hPa heights. It can be seen that the high correlation belt with values $\geqslant 0.3$ (significant at the 0.05 confidence level) spreads zonally from central Asia to central North Pacific, with two large value centers over Northeast China and the Aleutian Islands, respectively. The maximum correlation value was over 0.7 (significant at the 0.01 confidence level) over the first center. The correlation coefficient pattern over Asia and North Pacific (Fig. 4a) is similar to the 500-hPa height anomaly pattern over the same region (Fig. 3a), indicating that the summer temperature was positively correlated with the 500-hPa height anomaly in Northeast China, that is to say, the NESLT corresponded to the negative summer 500-hPa height anomalies in Northeast China, and vice versa.

4.3 Meridional circulation

Figures 5a and 5b are the cross-sections of vertical and meridional winds and temperature anomaly for A event years and high temperature years of Northeast China along 120°E, respectively. It is seen from Fig. 5a that the southward air flow from the polar region of Northern Hemisphere met the northward flow originated from the equatorial region over 50°–52°N, then ascended, and obviously converged in the mid-upper troposphere of 600–200 hPa. Correspondingly, a thick cold air layer at 850–250 hPa with a core cold air layer at 500–400 hPa, where the negative anomaly center was −1.5°C, controlled the whole Northeast China, and above the thick cold air layer was a warm tropopause with a warm core of +0.9°C at 150 hPa. However, in the summer high temperature years (Fig. 5b), the polar cold air could reach the vicinity of 75°N only at the tropopause, but the warm air originated from the equatorial region could advance northward within the planetary layer to the north of 50°N, indicating that the warm air at low levels was very strong. Over 40°–50°N, there was a warm core of 1.5°C, with its warm tongue extending upward to the mid-upper troposphere, and the relevant flow also ascended and advanced towards the vicinity of the polar region. The above reveals that the cold core of NESLT lay in the vicinity of 500 hPa in the middle troposphere, so we examine the evolution of 500-hPa circulation systems for the diagnosis and prediction of the NESLT events.

5. Decadal variability

5.1 Summer average temperature at Changchun and Harbin

Summer average temperature anomaly series at Changchun (Fig. 6a) and Harbin (Fig. 6b) clearly

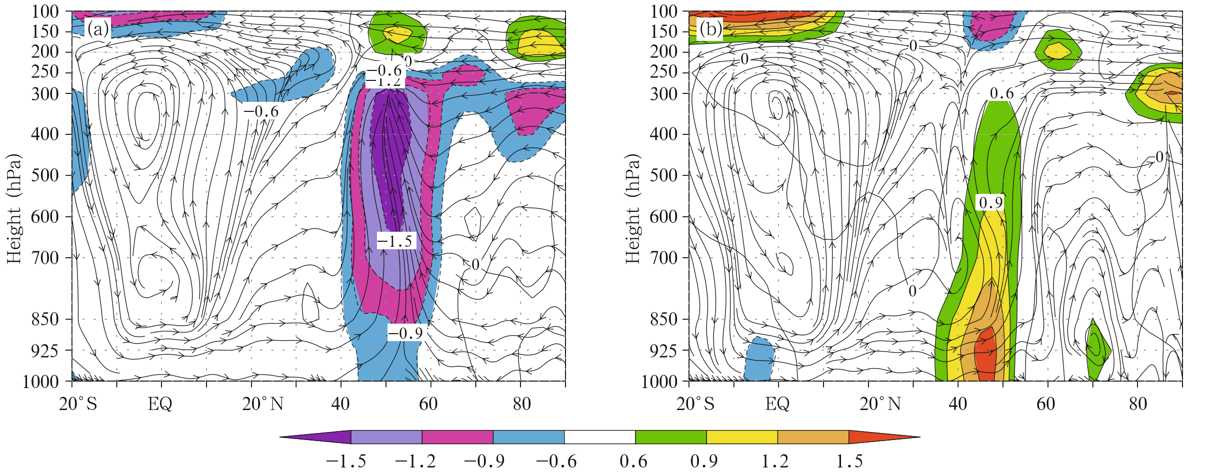

Fig. 5. Composite latitude-height cross-sections of wind and temperature anomaly (°C) over (a) A event years (1969, 1971, 1972, and 1976) and (b) typical summer high temperature years (1982, 1988, 1994, and 1997) of Northeast China along 120°E. Thick solid line with arrows denotes streamline of vertical and meridional winds; thin solid line with color shaded area denotes positive temperature anomalies; thin dashed line with color shaded area denotes negative temperature anomalies. The multi-year mean was calculated for 1958–1997.

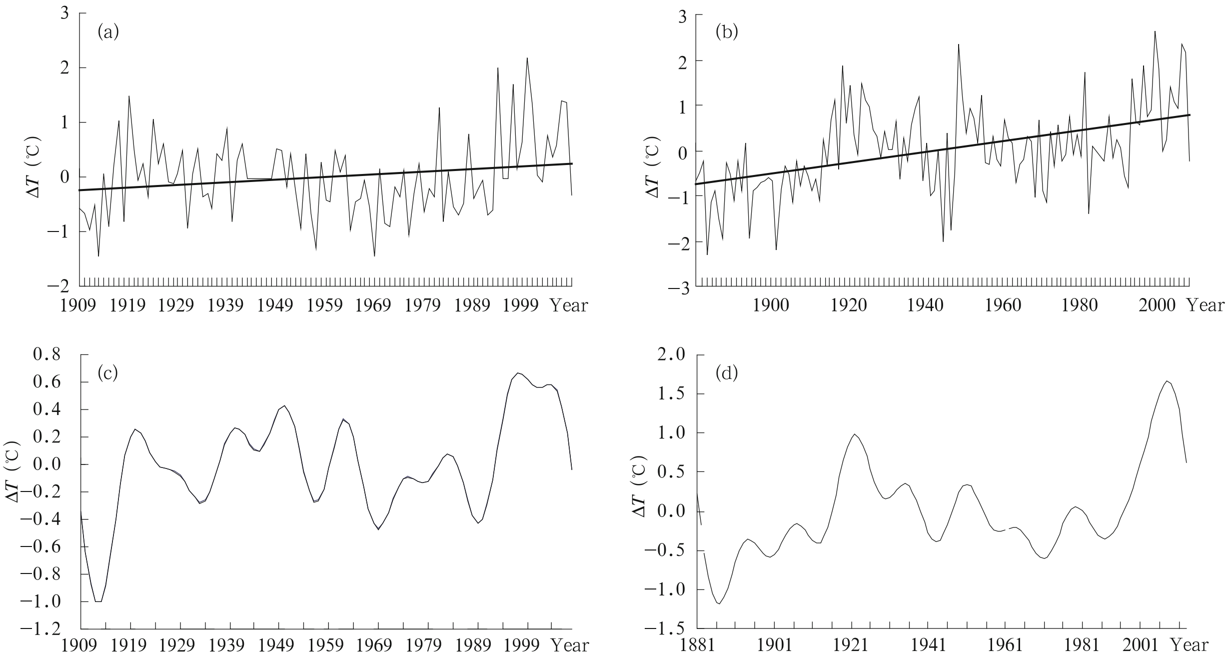

Fig. 6. (a, b) Summer average temperature anomaly series (thin solid line: temperature anomaly; thick solid line: linear trend) and (c, d) their interdecadal variations at (a, c) Changchun and (b, d) Harbin, respectively.

show that the temperature has exhibited a rising trend since the 1920s, and no obvious negative anomaly has occurred since 1994. However, in the summer of 2009, negative anomalies of –0.34 and –0.24°C occurred at Changchun and Harbin stations, respectively.

Analysis of the decadal component (⩾ 9 yr) of summer average temperature anomaly series (Figs. 6c and 6d) shows that the summer temperature of Harbin varies with an about 80-yr dominant period, e.g., a cold phase in 1881–1913, a warm phase in 1914–1954, a cold phase again in 1955–1992, and a warm phase in 1992–2008 (Fig. 6d). The dominant period for the summer temperature of Changchun is about 70 yr (Fig. 6c), e.g., a cold phase before 1918, a warm phase in 1919–1953, a cold phase again in 1954–1991, and a warm phase in 1991–2008. Most of the cold and warm phases of the two series corresponded and overlapped. Especially, in the late 20th century to the early 21th century, after the positive temperature anomaly has reached the peak value among the 100-yr temperature observations, the temperature series at the two stations both underwent a declining phase, with a declining rate of about 0.7–0.8°C (10 yr)$^{-1}$, that even exceeded the linear warming rate of 0.2°C (10 yr)$^{-1}$ during 1961–2000 (Yan, 2007).

Power spectrum analysis of the of summer average temperature series of Changchun (Fig. 7a) and Harbin stations (Fig. 7b) indicates that the temperature series of Changchun has 66- and 33-yr periods significant at the 0.05 confidence level (Fig. 7a); while the temperature series of Harbin has 82-, 3-, and 2.3-yr significant periods (Fig. 7b). This further confirms that the cold and warm phase alteration of about 30–40-yr is significant at the 0.05 confidence level.

5.2 Decadal variability of NPPV

The time series of North Pacific Polar Vortex (NPPV) area index for previous winter (relative to the summer of the indicated year; Fig. 8a) shows that after a period of rapid rising (1958–1963), the area index is low (1964–1992), and its variation is similar to that of the Changchun summer average temperature (1959–1992) (Fig. 6c). The NPPV area index for spring (Fig. 8b) is basically similar to that for previous winter (Fig. 8a), but no second peak appears after 1988, thereby indicating that the NPPV area index has strong persistence from the previous winter to spring. This persistent anomaly on the half-year scale might provide a precursor signal for short-term prediction of the anomalous East Asian summer climate.

5.3 Relations of Changchun and Harbin summer temperatures to decadal variations of NPPV and North Pacific SSTs

Table 3 shows that the correlations between summer average temperatures of Changchun and Harbin and the previous winter and spring SSTs of the west wind drift region and Nino 3+4 region did not pass their significance tests of the 0.05 confidence level, but those for summer and autumn SSTs (simultaneous or lagging) were significant at the 0.05 confidence level. After decomposing the summer average temperature time series of the two stations into interannual and decadal component series, it is found that the decadal

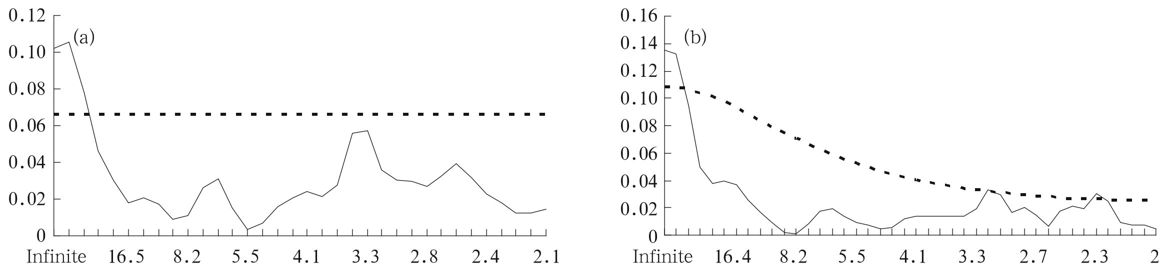

Fig. 7. Power spectra of observed yearly summer temperatures at (a) Changchun and (b) Harbin. Solid line: power spectrum value; dotted line: threshold line for $\alpha \geqslant 0.05$ level of significance.

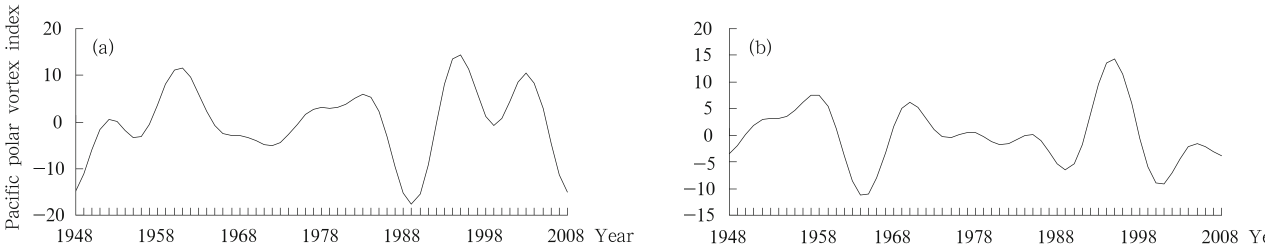

Fig. 8. Decadal variations of NPPV area indices for (a) previous winter and (b) spring.

Table 3. Correlation coefficients between North Pacific SST and the summer average temperatures of Changchun and Harbin

	SST location	Previous winter	Spring	Summer	Autumn
Changchun	West wind drift region*	–0.07	0.01	0.26	0.35
	Nino 3+4	–0.01	–0.01	–0.02	–0.04
Harbin	West wind drift region*	–0.02	0.08	0.33	0.34
	Nino 3+4	–0.03	–0.06	–0.05	–0.04

*Correlation coefficients for Changchun and Harbin were calculated based on the data of 1909–2005 and 1881–2005, respectively.

Table 4. Correlation coefficients of the interannual and decadal components of the seasonal average temperatures of Changchun and Harbin with the NPPV area index and North Pacific SSTs in four seasons

		NPPV area index*				North Pacific SST**							
						West wind drift region				Nino 3+4			
		Previous winter	Spring	Summer	Autumn	Previous winter	Spring	Summer	Autumn	Previous winter	Spring	Summer	Autumn
Changchun	Interannual component	0.08	0.05	**–0.28**	**–0.36**	**–0.21**	–0.14	–0.12	–0.02	**0.21**	0.15	0.08	0.10
	Decadal component	**0.56**	–0.08	–0.16	**0.23**	**0.24**	**0.23**	**0.40**	**0.53**	–0.15	–0.17	–0.07	–0.05
Harbin	Interannual component	0.06	0.02	–0.14	–0.16	0.04	0.04	–0.02	–0.02	**0.17**	0.08	–0.07	–0.02
	Decadal component	**0.26**	–0.09	–0.08	0.07	–0.11	0.02	**0.25**	0.07	0.08	0.10	0.09	**0.21**

*Correlation coefficients for Changchun and Harbin were both calculated based on the data of 1948–2008;

**Correlation coefficients for Changchun and Harbin were calculated based on the data of 1909–2005 and 1881–2005, respectively. Values in bold exceed the 0.05 cofindence level.

components of Changchun and Harbin summer temperatures are positively correlated with the previous winter NPPV area index at the 0.01 and 0.05 confidence level, respectively (Table 4); and that the interannual component of Changchun summer temperature is negatively correlated with the summer and autumn NPPV area indices, as well as previous winter SST of the west wind drift region, significant at the 0.05 confidence level. It is also known from Table 4 that the decadal component of Changchun summer temperature is positively correlated with those of all four season SSTs in the west wind drift region and those of the previous winter SST in the Nino 3+4 region, at the 0.05 confidence level; and the interdecadal component of Harbin summer temperature is also significantly correlated with that of the summer SST in the west wind drift region at the 0.05 confidence level. This indicates that the previous winter NPPV area index provides an important precursor signal for changes in both Changchun and Harbin summer temperatures on decadal scale; and changes in the previous winter SST in the west wind drift region are also important prophase signals for summer temperature changes at Changchun Station, and changes in the SST of Nino 3+4 region in previous winter also to some extent affect Changchun summer temperature. Besides, the SST anomaly over east-central equatorial Pacific in winter 2008 presented a La Niña pattern, which obviously weakened in the spring of 2009 (figure omitted).

6. Teleconnection between Northeast China summer temperature and NPO

6.1 Half-year-scale teleconnection

Figures 9a and 9b give the homogeneous correlation maps of the SVD1 of the previous winter 500-hPa geopotential height field in the NPO region and the summer average temperature field of 80 stations in Northeast China, respectively. The two maps both show an approximately south-north "+ –" phase distribution of correlation wavetrain; wherein a negative correlation region lies around the Aleutian Islands with its center value $\leqslant -0.8$ in the north of the islands, and a positive correlation center with its value $\geqslant 0.6$ lies in the eastern Pacific near 65°N (Fig. 9a). Correspondingly, the summer temperature showed consistent positive values over Northeast China, with correlation coefficients mostly from 0.7 to 0.9 (Fig. 9b);

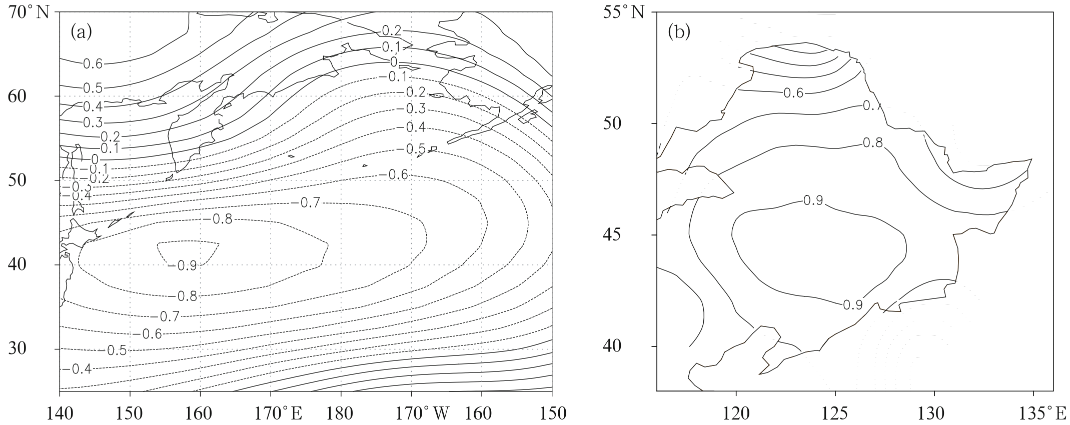

Fig. 9. Simultaneous correlation maps of the SVD1 of (a) the 500-hPa geopotential height field of the NPO region (25°–70°N, 140°E–150°W) in previous winter and (b) the summer average temperature field of 80 stations in Northeast China.

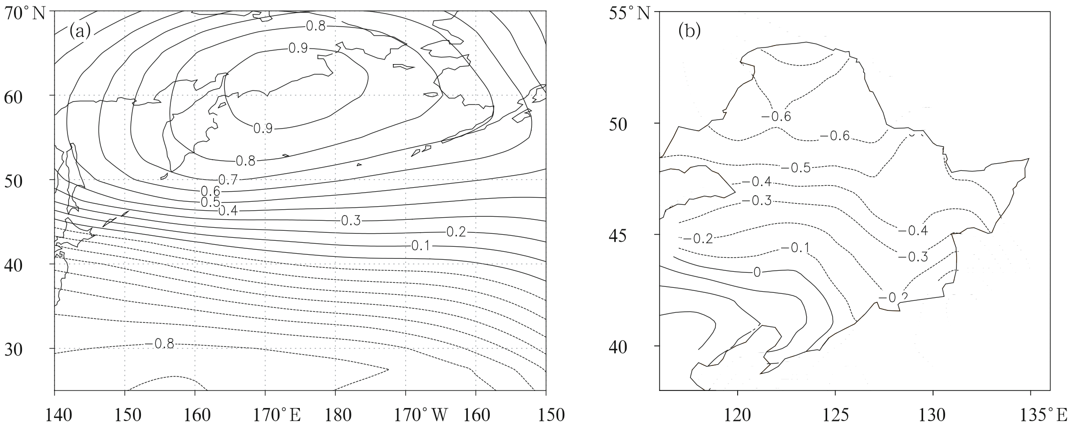

Fig. 10. As in Fig. 9, but for SVD2.

the half-year scale teleconnection of the two fields is significant at the 0.01 confidence level, and the contribution of SVD1 accounts for 75% (a very high weight) of the total sum of squared covariances.

The homogeneous correlation maps of the SVD2 (Figs. 10a and 10b) show a pattern opposite to that of the SVD1 (Figs. 9a and 9b). That is to say, over the Aleutian Islands and the Kamchatka Peninsula area, there is a large positive correlation region with its center values above 0.8; and over the smaller area south of 45°N, there is a negative correlation zone with its center value ⩽–0.8 (Fig. 10a). Correspondingly, Northeast China is dominated mostly by negative correlations, especially over Jilin and Heilongjiang provinces, and the correlation coefficients range from –0.25 to –0.50 with most of them passing the 0.05 confidence level (Fig. 10b). The correlation flow for the SVD2 is the same as the SVD1, i.e., if there is a north-south "+ –" (or "– +") phase distribution in the NPO region in the previous winter, the summer temperature in Northeast China will be lower (or higher). The variance contribution of the SVD2 accounts for 12% of the total covariance, and the contributions of the SVD1 and SVD2 account for 87% of the total covariance, which sufficiently indicates that the NPO phase distribution in previous winter is an important and strong precursor signal for the summer temperature of Northeast China. The anomalous phase of NPO might be a planetary-scale stable component that can be extracted from the atmospheric general circulation.

6.2 Similar NPO situations between 2009 and 1972

It can be seen from Figs. 11a and 11d that the

500-hPa height anomaly patterns of the previous winters of 1972 and 2009 are very similar, i.e., the Northern Hemispheric 500-hPa circulation basically showed a two-wave disturbance distribution, with the strongest positive anomaly center both over the sea south of the Aleutian Islands, and in the NPO region where there appeared a typical negative phase of the north-south "+ –" anomaly distribution of NPO. The positive anomaly center with its center value being 140 gpm in 2009 is slightly stronger than its counterpart in 1972, but the two-wave disturbance pattern in 1972 is clearer than that in 2009. Furthermore, there appeared also a stronger negative phase of North Atlantic Oscillation (NAO) over the Atlantic Ocean, relative to that in 1972.

Figures 11b and 11e show that the spring 500-hPa height anomaly patterns of 1972 and 2009 are also very similar: the negative phase disturbances of NPO still maintained over the mid-high latitudes of North Pacific, except that the positive anomaly center over the sea south of the Aleutian Islands was obviously weakened relative to that in the previous winter, but it was

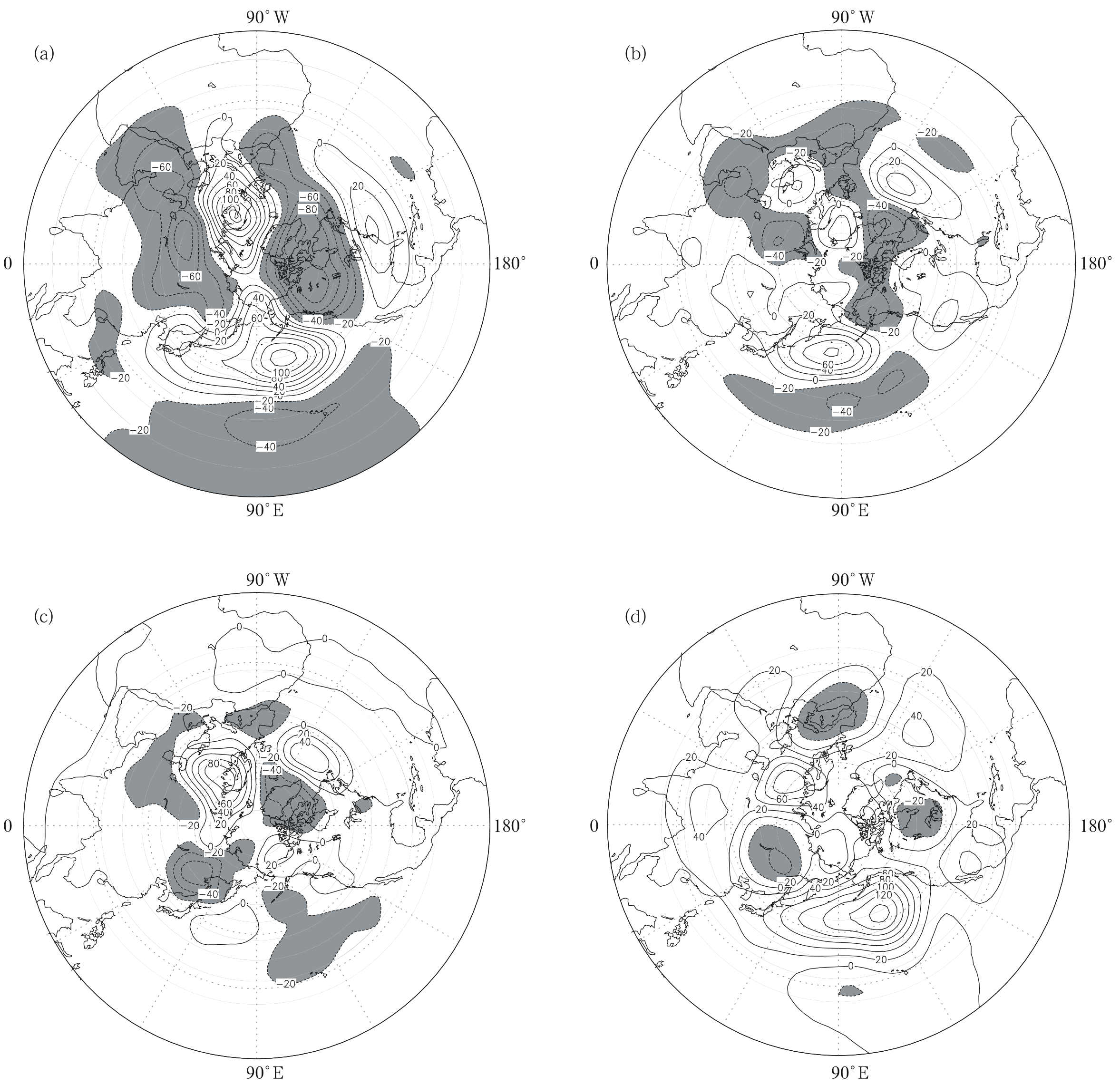

Fig. 11. 500-hPa geopotential height anomaly fields (gpm) in previous winter of (a) 1972 and (d) 2009, spring of (b) 1972 and (e) 2009, and (c) summer of 1972. Solid (dashed) line denotes positive (negative) anomaly; contour interval is 20; shadings indicate values less than or equal to –20.

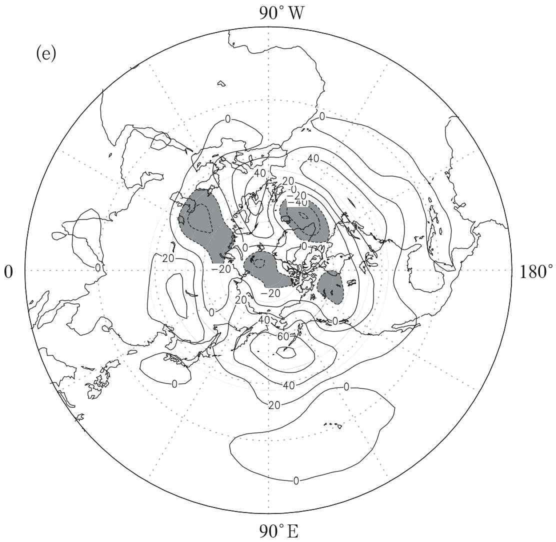

Fig. 11. (Continued.)

still the strongest spring disturbance center over the Northern Hemisphere. Therefore, the negative phases of NPO in the previous winter and spring of 1972 and 2009 were very strong and sustained for a half-year, which must have impacted the summer Northern Hemispheric 500-hPa circulation. In summer 1972, A event occurred in Northeast China (Table 2) with stronger negative temperature anomalies (Fig. 11c), but in summer 2009, the negative 500-hPa height anomaly center moved to the coastal region of Russia, east of its normal position (Fig. 2a), and the NESLT mainly happened in the central-eastern parts of Jilin and Heilongjiang provinces. The persistent negative phase of NPO over the previous winter and spring of 1972 and 2009 both resulted in the occurrence of NESLT events, again indicating that the anomalous phase of NPO is a stable planetary-scale signal worthy of notice.

6.3 Harmonic analysis of the preceding 500-hPa height field for anomalous NECV activities

Figure 12 shows the ultra-long wave disturbance distribution of 500-hPa height along 45°N during April–May 2009. The ultra-long wave (wavenumbers 1–3) trough always stayed over 120°–180°E especially the North Pacific region. It obviously shifted eastward only in early May and then distinctively retreated westward again in mid May. This is a typical precursor for anomalously strong activities of summer NECV (Shen et al., 2008), indicating the transformation of

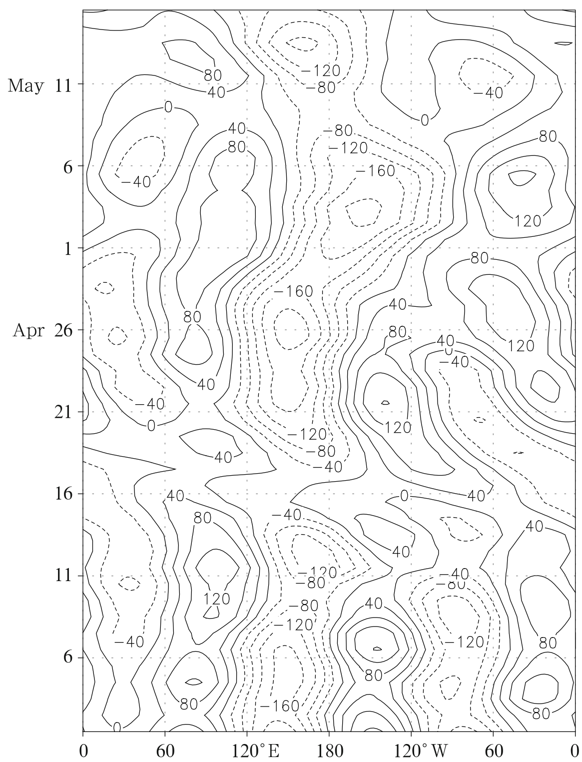

Fig. 12. Time-longitude cross-section showing the ultra-long wave disturbances of the 500-hPa geopotential height (gpm) along 45°N. Solid (dashed) line denotes positive (negative) value.

the North Pacific ultra-long wave disturbance trough along 45° N into a stationary wave disturbance trough, which is obviously related to the persistent north-south "+ –" anomaly wavetrain of the negative phase of NPO over the North Pacific region in spring, and is the major character of prophase circulation evolution or a precursor for the anomalous June NECV activities of 2009. The NECV days in June–July 2009 were 18 days more than normal, accounting for a percentage anomaly of 54%.

7. Conclusions and discussion

A summer low temperature event occurred in the central-northern part of Northeast China in 2009. The temperature anomaly at Changchun Station reached -0.49σ, characterizing a B event according to the NESLT classification given in this paper.

It is found that a strong NECV directly resulted in the NESLT in central-eastern Northeast China in summer 2009. Summer average temperatures of Harbin and Changchun were significantly correlated with concurrent 500-hPa height over Northeast China, with correlation coefficients of more than 0.7, significant at the 0.01 confidence level. Composite analysis reveals that the meridional circulation for typical NESLT years is featured with a deep cold air layer between 850 and 250 hPa over the whole Northeast China. The horizontal and vertical circulation reflect anomalously strong NECV activities directly responsible for NESLT events. During June–July 2009, 18 more NECV days appeared, accounting for a percentage anomaly of 54%; and the negative 500-hPa height anomaly directly resulted in the NESLT over the coastal region of Russia, east of its normal position.

The decadal components ($\geqslant 9$ yr) of observed 100-yr summer average temperature series at Harbin and Changchun exhibited a distinctive declining trend in the past decade, which provides an important decadal background for the NESLT of Jilin and Heilongjiang provinces in 2009. The power spectrum analyses of the temperature series of the two stations uncover that the series had a significant 30–40-yr cold/warm phase alteration and showed a remarkable declining trend in the period from the end of the 20th century to the beginning of the 21st century, with the declining rate of 0.8°C $(10 \text{ yr})^{-1}$ over 1999–2008, far greater than the linear warm rate of 0.2°C $(10 \text{ yr})^{-1}$ of Northeast China in response to the global warming over 1961–2000. The summer circulation anomaly over the mid-high latitudes of Northern Hemisphere in 2009 is almost opposite in sign (positive/negative) to that in 1994–2008 when no NESLT event happened. Meanwhile, in 2009, significant negative phase of AO and negative height anomalies over Northeast Asia, Aleutian Islands, and the North Atlantic occurred.

The decadal variation of previous winter NPPV activities is an important background condition for summer temperature change in Northeast China. The previous winter NPPV area index, which was significantly positively correlated with the summer temperatures of Changchun and Harbin, also showed a decadal declining trend. It is also known that the SST in the west wind drift region of North Pacific also affects the summer temperature in Northeast China, with its effect next secondary to that of the NPPV, and the SST in the east-central tropical Pacific has some impact as well.

The phase of NPO is an important precursor for summer temperature changes in Northeast China. This is also a planetary-scale stable atmospheric component in addition to the synoptic-scale chaotic component. The SVD1 and SVD2 of previous winter 500-hPa height fields in the NPO region and summer temperature fields at the 80 stations of Northeast China both reveal that the positive/negative phase of NPO was significantly correlated with the positive/negative anomaly of summer temperatures, with the covariance contributions of the SVD1 and SVD2 to the total covariance reaching 87%. In the previous winter of 2009, the negative phase of NPO was the strongest since the mid 1980s and it sustained into the spring of 2009. The evolution of NPO was very similar to that in 1972, when a severe NESLT event occurred in Northeast China. Therefore, occurrence of the 2009 NESLT event may hint that summer temperature in Northeast China might have entered a low temperature phase similar to that in the 1970s.

Harmonic analysis of April–May 500-hPa height along 45°N over North Pacific suggests that the ultra-long wave activities appearing as a form of stationary disturbances serve as a precursor for the anomalously strong activities of NECV in June–July 2009. The ultra-long wave disturbance trough over North Pacific was a stationary wave disturbance, which was related to the persistent negative phase of the north-south "+ –" anomaly wavetrain of NPO, and formed a prophase mid-high latitude circulation background in favor of the June–July unusually active NECVs of 2009.

This paper analyzed the decadal variation of the 100-yr temperature observations at Changchun and Harbin stations and the NPPV activities. The results showed a declining trend of summer temperature in the recent decade. On the annual and seasonal scale, the previous winter and spring precursor signals of the air-sea system over North Pacific favorable for the occurrence of NESLT and NECV are identified. On the intraseasonal and monthly scale, the lower frequency signal of June–July 500-hPa height in favor of NECV is uncovered by the power spectrum analysis. In early June 2009, we used the above data and methods, with reference to the 10–16-day 500-hPa height forecast (in which abnormally more frequent NECV activities were found), issued a summer low temperature warning. This is a successful effort on the prediction of NESLT.

Overall, this paper investigated the large-scale circulation features of the 2009 NESLT event. Meanwhile, composite analysis was performed to identify the decadal background favorable for the occurrence of NESLT, the relationships between NESLT/NECV activity and prophase changes in the air-sea system over the North Pacific region, and how to predict the NESLT event of 2009 using multi-spatiotemporal scale predictors. However, the physical mechanism of the NESLT and the sea-air system association is not clear. Is the NESLT event of 2009 only an isolated case, or an early warning signal for a new phase of massive occurrences of such events? Further studies are needed to address those issues.

Acknowledgments. The authors would like to thank Prof. Ding Yihui for his valuable advice; thanks also go to the two anonymous reviewers for their valuable comments. Contributions from Gao Zongting, Chen Changsheng, Guo Chunming, Su lixin, Tu Gang, Sui Bo, et al. of the Institute of Meteorological Science of Jilin Province were also appreciated.

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