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The Interannual Variation in Monthly Temperature over Northeast China during Summer

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ABSTRACT

The interannual variations of summer surface air temperature over Northeast China (NEC) were investigated through a month-to-month analysis from May to August. The results suggested that the warmer temperature over NEC is related to a local positive 500-hPa geopotential height anomaly for all four months. However, the teleconnection patterns of atmospheric circulation anomalies associated with the monthly surface air temperature over NEC behave as a distinguished subseasonal variation, although the local positive height anomaly is common from month to month. In May and June, the teleconnection pattern is characterized by a wave train in the upper and middle troposphere from the Indian Peninsula to NEC. This wave train is stronger in June than in May, possibly due to the positive feedback between the wave train and the South Asian rainfall anomaly in June, when the South Asian summer monsoon has been established. In July and August, however, the teleconnection pattern associated with the NEC temperature anomalies is characterized by an East Asia/Pacific (EAP) or Pacific/Japan (PJ) pattern, with the existence of precipitation anomalies over the Philippine Sea and the South China Sea. This pattern is much clearer in July corresponding to the stronger convection over the Philippine Sea compared to that in August.

Key words: surface air temperature, Northeast China, interannual variation, subseasonal variation, teleconnection patterns.

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1. Introduction

The interannual variation is one of the most remarkable features of the summer temperature over Northeast China (NEC), and it is the cause of damaging cold or extreme hot weather over NEC (Ding, 1980; Sun et al., 1983). For the whole summer, the anomalous NEC temperature is mainly controlled by the anomalous geopotential height over NEC (Northeast China Cold Summer Research Group, 1979). If NEC is covered by negative height anomalies, the cold air is active and flows southward from the high latitudes into Northeast China, resulting in a cold summer.

The teleconnection patterns of the atmospheric circulation anomalies have been investigated in previous studies. Zhang et al. (1985) proposed the connection between the variations of the polar vortex and the summer temperature over NEC, which indicated that the high temperature over NEC is related to the strong polar vortex. In addition, Gu and Yang (2006) suggested that when the polar vortex consistently contracts, and the total area of the polar vortex reduces, the NEC temperature becomes warmer. Cui et al. (2007) mentioned that the anomalies of the western North Pacific subtropical high (WNPSH) is another influencing factor on the NEC summer temperature. A strong and northwestward WNPSH contributes to a warm summer over NEC, while a weak and southeastward WNPSH is related to a cold NEC summer. Moreover, the interannual variation of surface air temperature over NEC can be modulated by the sea ice cover over the eastern Siberian Sea (Fan and Wang, 2010), the ENSO events (Sun and Wang, 2006) and the Northern Hemisphere Annular Mode (NAM) (Wang and Sun, 2009).

Also, the northeast cold vortex (NECV), which has crucial impacts on the climate over NEC, has a remarkable teleconnection with the North Pacific Oscillation (NPO) (Liu et al., 2002, 2003; Lian et al., 2007, 2013; Shen et al., 2012). The negative phase of the NPO provides a favorable background for the activities of the NECV. He et al. (2006) also inferred that the strong (weak) NAM is associated with the high (low) frequency of the NECV in summer. It should be mentioned that both the negative phase of the NPO and the strong NAM mode exhibit a positive height anomaly over NEC.

The atmospheric patterns contributing to the changes of summer temperature over NEC mentioned above have strong subseasonal variation. For example, the changes of polar vor-

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tex can be observed on a daily-to-monthly timescale. The intensity and position of the WNPSH has a strong seasonal evolution in summer (e.g., Wu and Wang, 2001; Su and Xue, 2010), which might result in uncertainty about the impacts of the WNPSH during the whole summer (Ye and Lu, 2011). In addition, like the atmospheric modes, the variations of the NPO and the NAM on a subseasonal timescale should be noted.

Recently, Shen et al. (2011) indicated that the NEC summer precipitation and associated circulation anomalies are quite different between early summer and mid-summer. In the early summer, an anomalous cyclonic circulation in the troposphere is in favor of the occurrence of the NECV, and results in an increase of precipitation over NEC. However, the northwestward shift of the WNPSH is the main contributor to the NEC precipitation in mid-summer. These distinguished differences between early- and mid-summer indicate the subseasonal variation of summer precipitation over NEC.

However, previous studies on the changes of temperature over NEC have used the seasonal average to represent the summer time and therefore seldom taken subseasonal variation into consideration. Actually, according to the previous studies mentioned above, the interannual variations of precipitation and associated large-scale circulation have strong subseasonal variability (Shen et al., 2011). Also, the teleconnection patterns modulating the NEC summer temperature are monthly-dependent. But what about the interannual variation of the NEC surface air temperature on the monthly timescale? What are the circulation anomalies associated with the interannual variation of the monthly temperature over NEC? What is the difference in the teleconnection patterns among these months? To answer these questions, we examined the interannual variations of monthly NEC surface air temperature and the circulation anomalies corresponding to monthly NEC temperature variability. The rest of this paper is organized as follows. We introduce the datasets and methods used in this work in section 2. In section 3, the main features of the interannual variation of surface air temperature over NEC from May to August are shown. In section 4, the atmospheric circulation anomalies associated with the monthly NEC temperature anomalies are shown. A summary is given in section 5.

2. Datasets and methods

This study used the monthly mean surface air temperature from 160 stations in China from 1979 to 2009, which was provided by the National Climate Center of the China Meteorological Administration. Here, NEC is defined as the region east of 110°E and north of 38°N in China, which includes Heilongjiang Province, Jilin Province, Liaoning Province and the northeast part of Inner Mongolia Province. There are 27 stations in this region (Fig. 1), over which the surface air temperature was averaged to represent the NEC temperature (NECT) index.

The monthly mean NCEP/DOE Reanalysis II datasets from 1979 to 2009 (Kalnay et al., 1996) were used to obtain the atmospheric circulation variables including surface air temperature, 500-hPa geopotential height, and 850-hPa and 200-hPa horizontal winds. The monthly mean precipitation was from Global Precipitation Climatology Project (GPCP) data for the same period.

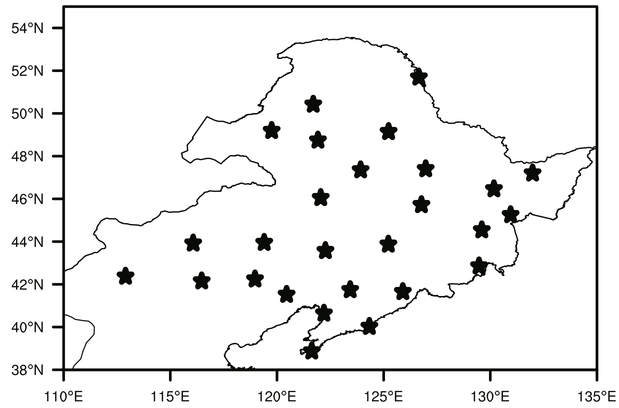

Fig. 1. Distribution of the 27 stations (east of 110°E and north of 38°N in China) used in obtaining the area-mean temperature for Northeast China.

The summer season in this study is from May to August. The temperature and associated atmospheric circulation anomalies were analyzed in each month separately to highlight the month-to-month difference in the interannual variation of NEC summer temperature and associated circulation anomalies. Considering that there is an appreciable decadal variation in NEC summer temperature (Sun and Wang, 2006), we focused on the interannual variability in this study and obtained the component of interannual variability by applying a 9-yr Gaussian filter.

3. The interannual variation in monthly temperature over NEC

Figure 2 shows the time series of the NECT index in May, June, July and August. All four original time series (curved line) show not only a clear interannual variation, but also a decadal variation and a long-term trend, which were ignored in this study. Thus, a 9-yr Gaussian filter was applied to highlight the interannual variation of monthly temperature over NEC (bars) and to remove the decadal variations and the linear trend. The linear warming trend exists in all four months. The correlation coefficients between the NECT index and the time (or year) are 0.36 for May, 0.31 for June, 0.36 for July and 0.37 for August, indicating that NEC temperature has a warming trend. The warming trend is significant at the 95% confidence level for May, July and August.

The interannual standard deviations for the four months are 0.80°C (May), 0.92°C (June), 0.61°C (July) and 0.69°C (August), and the ratios of the interannual variance to the total variance are 80.4% (May), 81.4% (June), 69.2% (July) and 82.3% (August), which also indicate that the interannual

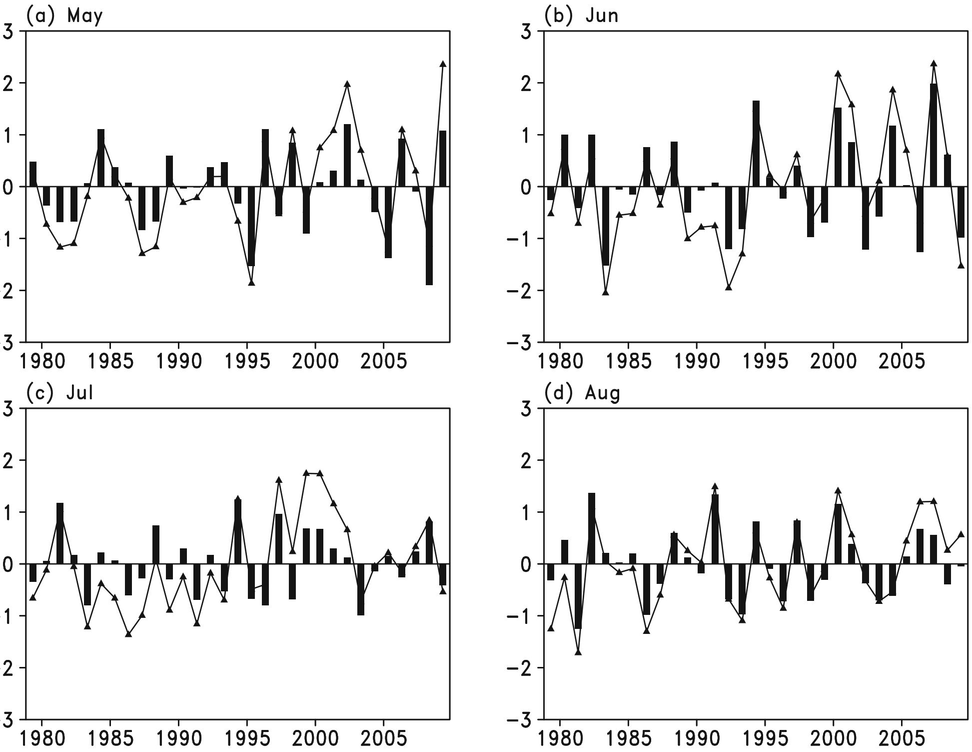

Fig. 2. Time series of NECT index (units: °C) for (a) May, (b) June, (c) July and (d) August. The NECT index was obtained by averaging the surface air temperature at the 27 stations shown in Fig. 1. The curved lines represent the original temperature anomalies, and the bars represent the ones using the 9-yr Gaussian filter.

variation dominates for the monthly temperature anomalies over NEC. In addition, for about 1/3 of the years of the entire period (11 years for May and August, 12 years for June, and 13 years for July) the temperature anomalies are above one standard deviation or below minus-one standard deviation.

Figure 3 shows the regression patterns of the surface air temperature on the NECT index in each month, which suggest that the NECT index we chose can well represent the monthly temperature anomalies over NEC. The notable interannual variation of monthly temperature is not limited to being only over NEC, but also extends to a relatively large area over Northeast Asia from southeast of Lake Baikal eastward to the Sea of Japan. The patterns are similar in May, June and August. In July, besides these significant signals over Northeast Asia, there is another linked center over the east of Japan, which results in a zonal extended distribution of the temperature anomalies. Additionally, there are only a few scattered anomalies over other regions.

The temperature anomalies are accompanied by precipitation anomalies over NEC (Fig. 4). Generally speaking, the positive temperature anomalies over NEC are associated with negative precipitation anomalies locally, since the lack of summer rainfall over NEC implies the enhancement of solar radiation and descending motions, which result in a higher temperature there (Trenberth and Shea, 2005; Wu et al., 2013). In May and June, the negative precipitation anomalies over NEC are consistent with the local positive temperature. In addition, there is a weak positive center near the Bay of Bengal in May, and these positive precipitation anomalies extend to the Arabian Sea, Indian Peninsula and east of the Bay of Bengal in June, which may be related to sufficient water vapor and favorable circulation conditions provided by the establishment of the South Asian summer monsoon in June.

The distributions of precipitation anomalies are different in July (Fig. 4c). The negative precipitation anomalies over NEC are weakly negative. The significant and strongly negative precipitation anomalies appear over subtropical East Asia, i.e., a banded region from central China northeastward to the Sea of Japan. Also, there are remarkable positive precipitation anomalies over the Philippine Sea and the South China Sea, which form a see-saw pattern with the northern precipitation anomalies. This see-saw pattern between tropical and subtropical precipitation anomalies can also be seen in August, but is neither significant nor well organized. The correlation coefficient between the NECT index and the precipitation anomalies over the tropical region (15°–30°N, 110°–160°E) is 0.58 in July, which is significant at the 99% confidence level, but is much weakened in August (0.29). Besides, there are some positive anomalies east of the Indian Peninsula and the Bay of Bengal in August, which share some similarities with those in June.

The negative precipitation anomalies over NEC associated with the NECT are much weaker in July and August than in May and June, which indicates that the negative temperature–precipitation correlation over NEC is stronger in May and June. This difference between May–June and

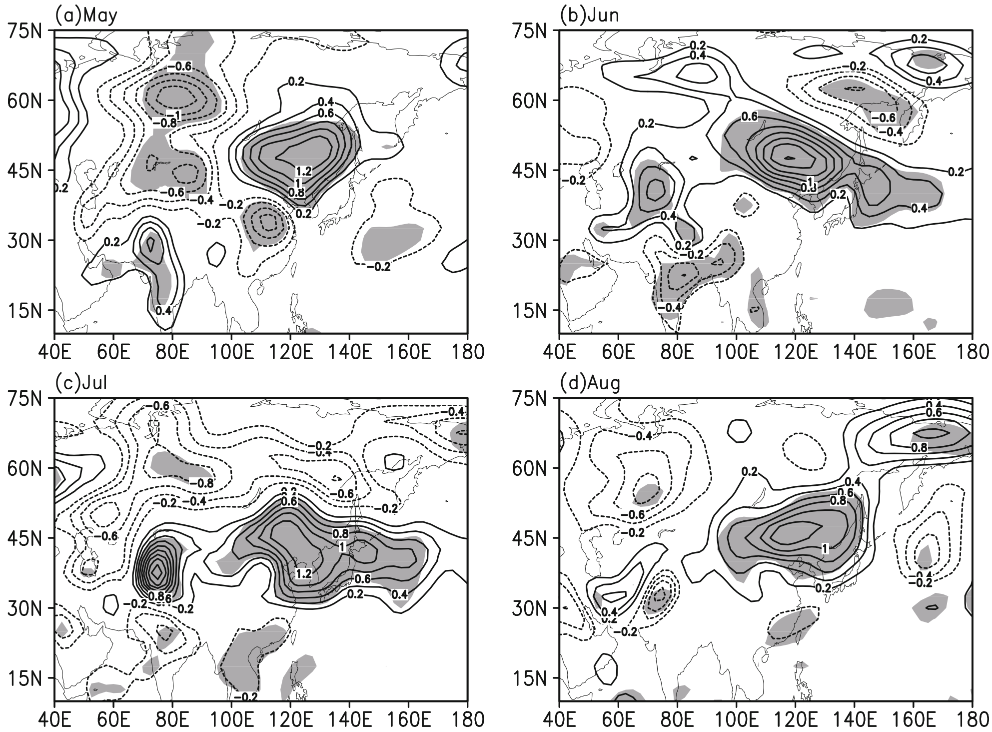

Fig. 3. Regression of surface temperature anomalies (units: °C) onto the NECT index for (a) May, (b) June, (c) July and (d) August. Shading indicates the regions where the anomalies are significant at 95% confidence level using the F-test.

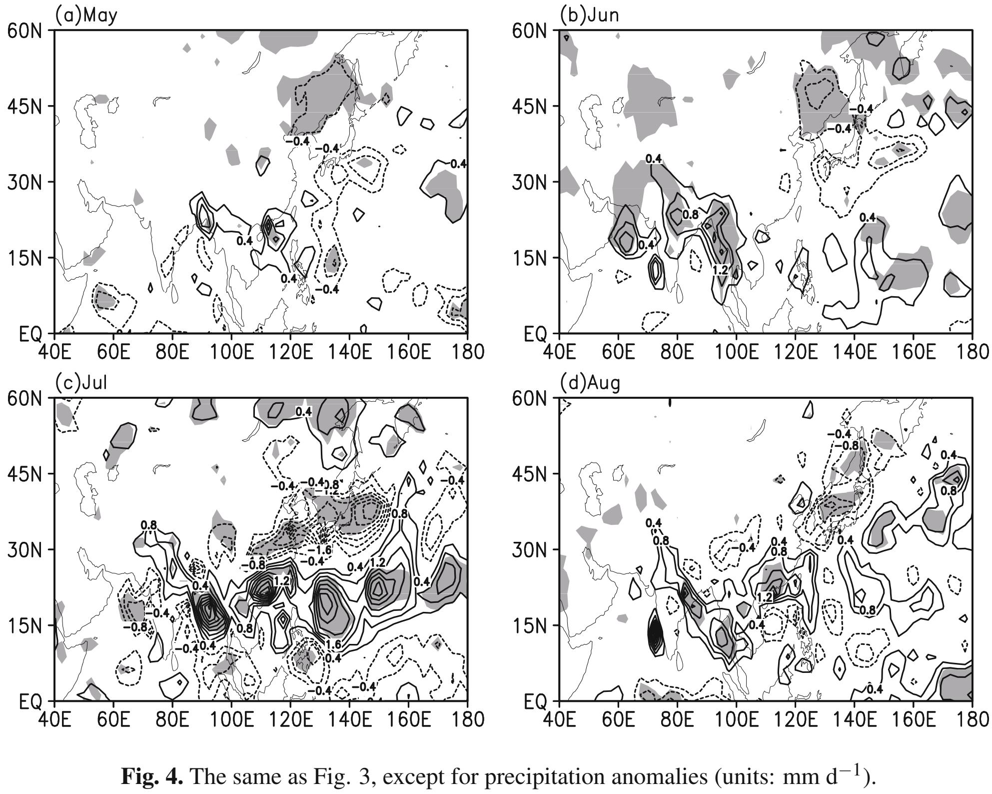

Fig. 4. The same as Fig. 3, except for precipitation anomalies (units: mm d^{-1}).

July–August can be explained as follows. Since the amount of precipitation is relatively small in May and June over NEC, the soil moisture is less and the Bowen ratio (ratio of sensible to latent heat fluxes) is high, and thus the surface air temperatures increases as the precipitation-related evaporation is reduced (Trenberth and Shea, 2005). However, in July and August, which is the rainy season in NEC, the water vapor from the tropical regions can be transported to NEC (Wang and Chen, 2012) and precipitation is much greater than that in May and June (e.g., Shen et al., 2011). Therefore, the Bowen ratio is low, and the surface temperatures are not so sensitive to evaporation. Furthermore, the lower-tropospheric southerlies transport both water vapor and warm air into NEC in these two months, and thus tend to result in more precipitation and a higher air temperature, which further weaken the negative temperature–precipitation correlation.

In summary, the precipitation patterns are consistent in May and June. They both show negative precipitation anomalies over NEC and positive ones over South Asia. The anomalous positive precipitation is much stronger in June against the background of the establishment of the South Asian summer monsoon. In July, on the other hand, there is a see-saw pattern of anomalous precipitation over the Philippine Sea and over an area east of NEC, which implies a linkage between mid- and low -latitudes. The distributions of precipitation anomalies in August exhibit a middle state between June and July. The weak positive precipitation anomalies over the Philippine Sea and the South China Sea are similar to those in July, while the positive precipitation anomalies over South Asia imply some similarities with those in June.

4. Atmospheric circulation anomalies associated with the anomalous NEC temperature

The lower-tropospheric circulations associated with the monthly air surface temperature exhibit a clear seasonal variation (Fig. 5). The anticyclonic circulation anomalies over NEC related to the positive temperature anomalies are significant in May and June, but extend eastward in July and August. The southerly winds in the west of these anticyclonic circulations prevent the cold air in the high latitude flowing southward and result in a higher than normal temperature over NEC. Also, the anomalous anticyclonic circulations suppress the activities of the NECV and lead to the decrease of precipitation over NEC (Shen et al., 2011). In addition, there are cyclonic circulation anomalies over the Philippine Sea in July (Fig. 5c) which are related to the remarkable positive precipitation there (Fig. 4c). The easterly wind anomalies north of the anomalous cyclonic circulation strengthen the anticyclonic circulation anomalies over NEC, which indicates the linkage of the circulation anomalies between the low and mid-latitudes in July.

There are positive geopotential height anomalies at 500-hPa over NEC associated with the warmer surface air temperature for all four months (Fig. 6). The positive height anomaly is roughly south of 50°N, compared with the negative height anomaly north of 50°N. This is consistent with the Northeast China Cold Summer Research Group (1979), who suggested that the summer temperature anomalies over NEC are mainly controlled by the contrast between the local geopotential height anomaly and that north of NEC. In addition, some previous studies suggested that the height anomalies over NEC are affected by remote factors, such as El Niño events (Lian and An, 1998; Wu et al., 2010) and SST anomalies over the North Atlantic Ocean (Wu et al., 2011).

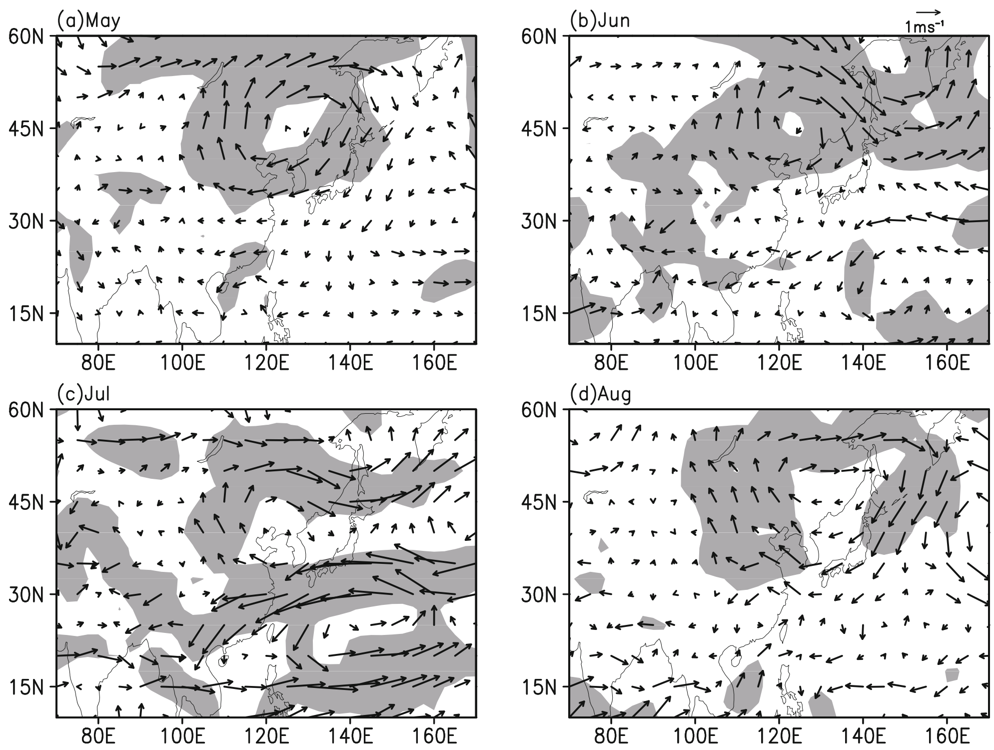

Fig. 5. The same as Fig. 3, except for 850-hPa wind anomalies (units: m s^{-1}). The shading indicates that either the meridional or the zonal wind anomalies are significant at a 95% confidence level.

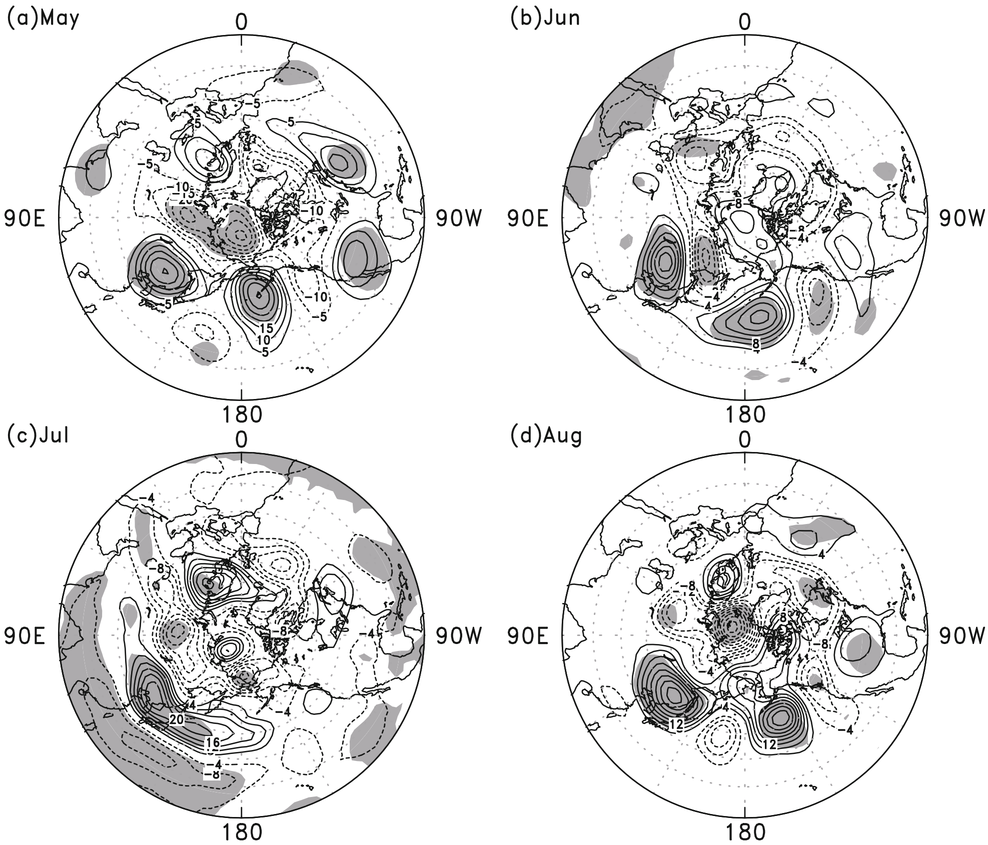

Fig. 6. The same as Fig. 3, except for 500-hPa geopotential height anomalies (units: m).

The close relationship between 500-hPa geopotential height anomalies and the surface air temperature anomalies over NEC is apparent from the data shown in Table 1. The correlation coefficients between them are significant at the 99% confidence level for all four months, and this positive correlation can be explained as follows. The positive height anomaly increases the input solar radiation and warms up the air mass by sinking, and therefore leads to a higher than normal surface air temperature over NEC. On the contrary, the negative height anomaly means that the ascent motions are active, which is in favor of convections and the cold air temperature over NEC.

On the other hand, all four months show a negative correlation between the 500-hPa geopotential height anomalies averaged over NEC and the persistent days of the NECV in each month, and the correlation coefficients are significant at the 95% confidence level in June, July and August (Table 1). This is consistent with Hu et al. (2010), who suggested that the positive 500-hPa height anomaly over NEC provides an unfavorable background for the occurrence of the NECV. Furthermore, the NECV can affect the surface air temperature through modulating the local precipitation. The presence (lack) of the NECV induces (reduces) the precipitation, which contributes to a colder (warmer) temperature over NEC. This process is demonstrated by the negative correlation between the monthly NECT index and the persistent days of the NECV, although the correlation coefficient is only significant in July, which implies that this process varies from month to month.

Table 1. Correlation coefficients among the 500-hPa geopotential height anomalies averaged over the region (40°–50°N, 110°–130°E) (H), the NECT index (T) and the days the cold vortex occurred (CV) in each month. One (two) asterisk(s) represents the correlation being significant at the 95% (99%) confidence level using the t-test.

	H&T	CV&H	CV&H
May	0.82**	−0.23	−0.20
Jun.	0.86**	−0.25	−0.14
Jul.	0.78**	−0.45*	−0.45*
Aug.	0.82**	−0.41*	−0.26

The patterns of 500-hPa geopotential height anomalies associated with the monthly temperature over NEC are similar in May, June and August. They are all characterized as several positive centers in the mid-latitudes and negative anomalies over the polar region. The pattern correlation coefficients among May, June and August in the northeastern hemisphere are 0.35 (May vs. June), 0.67 (May vs. August) and 0.37 (June vs. August). This similarity in circulation anomalies is consistent with the similar distributions of surface air temperature shown in Figs. 3a, b and d. In addition, there are positive signals near the Arabian Sea in May and June, which correspond with the precipitation anomalies there (Figs. 4a and b).

However, the circulation anomalies are quite different in July (Fig. 6c), where they behave as a meridional wave pattern with negative height anomalies in the western North Pacific and positive anomalies in the Sea of Japan. This pattern is known as the East Asia/Pacific (EAP) or Pacific/Japan (PJ) pattern (e.g., Nitta, 1987; Huang and Sun, 1992), which corresponds with the strong convection over the Philippine Sea and the South China Sea (Fig. 4c). Thus, the precipitation anomalies over the subtropical region in July plays a key role in modulating the temperature anomalies over NEC through intensifying the EAP or PJ pattern, which makes the teleconnection pattern associated with the anomalous NEC temperature unique in July compared with that in May and June. This is consistent with Lu (2004), who suggested that the EAP or PJ pattern contributed by the convection over the Philippine Sea is stronger in mid-summer.

The 200-hPa meridional wind anomalies associated with the NECT index are shown in Fig. 7. A clear and well-organized wave train related to the monthly temperature anomalies over NEC can be seen in May and June (Figs. 7a and b). This wave train is significant over the regions from the Indian subcontinent to the eastern Pacific, which leads to the positive geopotential height anomalies over NEC. This wave train is much clearer in June than in May because of positive feedback between the wave train and the precipitation anomalies over South Asia in June, when the South Asian summer monsoon has been established. This positive feedback is achieved by the strong convection over South Asia, triggered by a wave train extending from the northeastern Atlantic to East Asia, which could excite a Rossby wave and, in turn, reinforce the wave train (Ding and Wang, 2005). The correlation coefficient between the Indian summer rainfall [averaged over the region (10°–20°N, 60°–100°E)] and the NECT index in June is 0.38 (significant at the 95% confidence level), which supports the theory that the more South Asian rainfall in June, the higher the surface air temperature over NEC.

The upper-tropospheric wave train in July and August is not as well organized as that in May and June. In August, the strong 200-hPa meridional wind anomalies are located over NEC (Fig. 7d), and with weak negative ones over the Indian subcontinent. But in July, the wave train entirely disappears, and only a few significant centers could be caused by the stochastic disturbance. In short, the meridional wind anomalies related to the temperature anomalies over NEC are different in the four months.

Unlike the meridional wind, the 200-hPa zonal wind anomalies show an identical weakness to the subtropical westerly jet over East Asia when the surface air temperature is higher over NEC for all four months (Fig. 8). In May and June, the position of the westerly jet is around 38°N, and the anomalous anticyclonic wind shear north of the jet axis is in favor of the establishment of a positive height anomaly over NEC, which contributes to the warmer temperature over

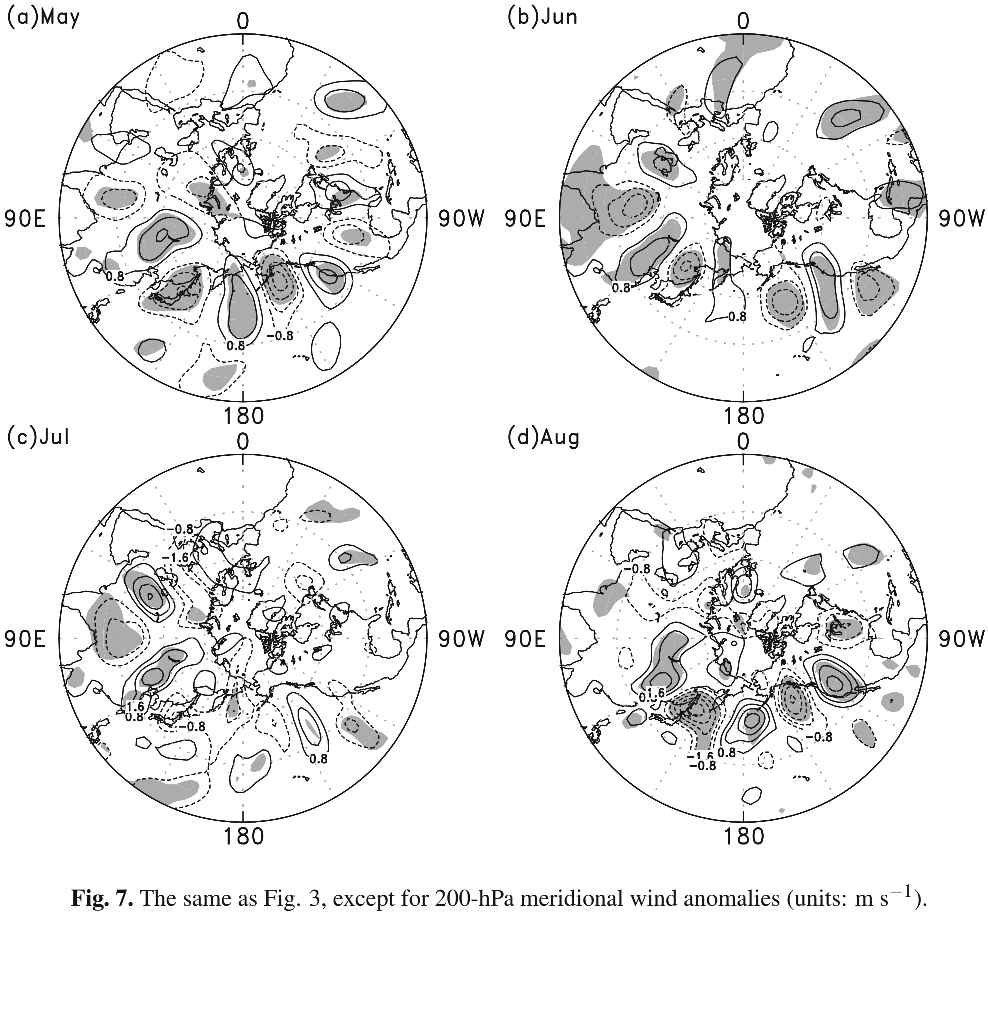

Fig. 7. The same as Fig. 3, except for 200-hPa meridional wind anomalies (units: m s^{-1}).

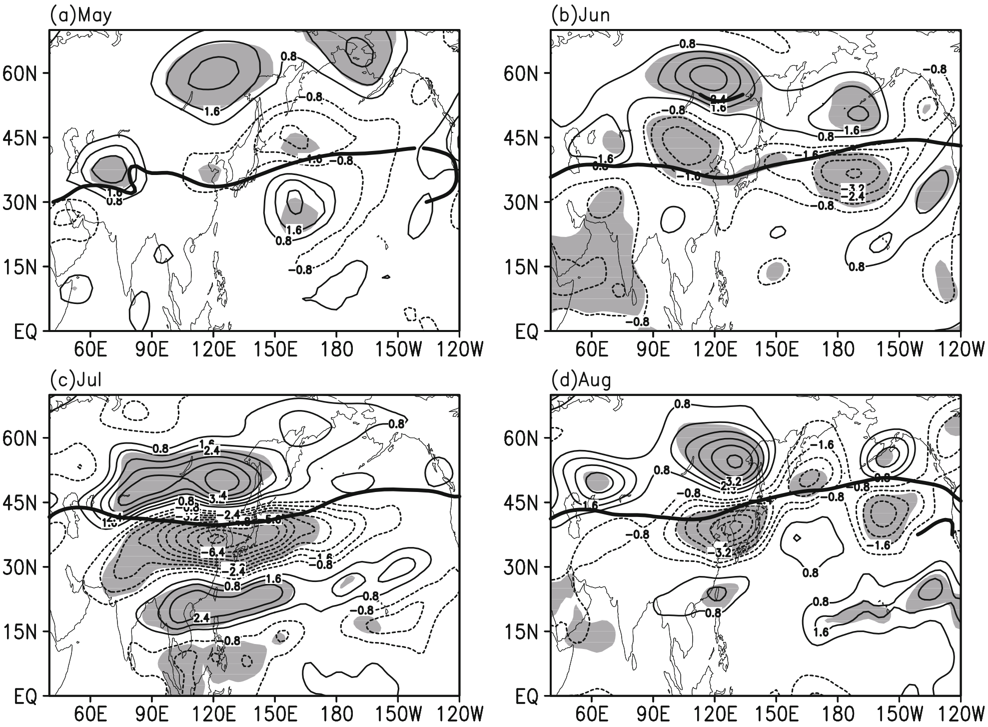

Fig. 8. The same as Fig. 3, except for 200-hPa zonal wind anomalies (units: m s^{-1}). The bold lines represent the position of the climatological subtropical westerly jet.

NEC. In July and August, the westerly jet is northward to 45°N, and an EAP or PJ pattern is clear over East Asia. Particularly in July, the distinguished EAP or PJ pattern leads to the zonally-extended circulation anomalies over NEC, which are consistent with the zonal distributions of temperature (Fig. 3c) and precipitation anomalies (Fig. 4c). This pattern indicates the close relationship between the subtropical convection and temperature anomalies over the mid-latitudes in July. Furthermore, the main system of the EAP or PJ pattern is eastward and with small extent in August, which is consistent with the weak and eastward precipitation anomalies over the Philippine Sea shown in Fig. 4d. This implies that the impacts from low latitudes on the temperature over NEC also exist in August, but the roles are weakened.

The pattern of circulation anomalies associated with the NECT index in July is clearly different to that in May, June and August. The possible reasons for this difference may be as follows. On the one hand, the meridional teleconnection over East Asia and the western North Pacific is clearer in July and August than in early summer, which is due to the difference in the wind shear over the tropical western North Pacific (Lu, 2004). Thus, there are wave-like zonal wind anomalies over East Asia and the western Pacific and precipitation anomalies over the tropical western North Pacific in July and August, but these wind and precipitation anomalies are much weaker in May and June (Figs. 4 and 8). On the other hand, the EAP or PJ pattern is quite robust in July but much weaker in August. This might be explained by the role of subtropical East Asian precipitation anomalies in maintaining the meridional teleconnection suggested by Lu and Lin (2009). The significant negative precipitation anomaly (Fig. 4c) over the subtropical East Asia in July plays a role in maintaining the EAP or PJ pattern, but this role is much suppressed in August due to the weaker subtropical precipitation anomaly (Fig. 4d). The reason for the weakness of the subtropical precipitation anomaly in August might be that the subtropical East Asian rainy season (meiyu season) ends during this period, and thus the interannual variability in precipitation is considerably suppressed.

5. Summary

This study investigated the interannual variations in monthly surface air temperature over NEC and associated atmospheric circulation anomalies from May to August during 1979–2009, using data and reanalysis datasets from 160 stations. All four months show significant interannual variations of surface air temperature over NEC, which explain most of the total variations. Furthermore, the notable interannual variation of monthly temperature is not limited to being only over NEC, but also extends to a relatively large area over Northeast Asia from southeast of Lake Baikal to the northwestern Pacific, over which identical interannual variations are present (Fig. 1).

In addition, the high temperature anomalies over NEC are related to the positive 500-hPa geopotential height anomaly locally in each month, since the positive height anomaly enhances the input solar radiation and warms up the air mass by sinking, and therefore leads to a higher than normal surface air temperature over NEC. Also, the positive height anomaly provides an unfavorable background for the occurrence of the NECV, which contributes to the warm temperature through reducing the local precipitation.

The teleconnection patterns associated with the monthly surface air temperature over NEC vary from month to month. In May and June, the warm temperature and positive height anomalies are related to a wave train from the Indian Peninsula to NEC. This wave train is further strengthened through the positive feedback between the wave train and the strong precipitation anomalies over South Asia in June when the South Asian summer monsoon has been established.

The patterns are quite different in July. An EAP or PJ pattern intensified by the strong convection over the Philippine Sea and the South China Sea responds to the temperature anomalies over NEC. This pattern also exists in August but is much weaker and eastward. Besides, the circulation anomalies associated with the NEC temperature anomalies in August also show some similarities with those in May and June. The teleconnection patterns in July are quite different to those in the other three months. This can be explained by the seasonal changes in the intensity of both the meridional teleconnection and the subtropical precipitation anomaly.

The results obtained by this study suggest that the interannual variation of the monthly surface air temperature and associated circulation anomalies are monthly-dependent. Given the fact that the teleconnection patterns related to the monthly surface air temperature are different in the four months, the strong subseasonal variation should be noted for the prediction of summer temperature over NEC.

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