ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 29, NO. 2, 2012, 295–306

Interannual Variation of Tropical Night Frequency in Beijing and Associated Large-Scale Circulation Background

Jong-Kil PARK[1], LU Riyu*[2] (陆日宇), LI Chaofan[2] (李超凡), and Eun Byul KIM[1]

[1] *Department of Atmospheric Environment Information Engineering, Atmospheric Environment Information Research Center, Inje University, Gimhae* 621–749, *Korea*

[2] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

(Received 2 August 2011; revised 20 October 2011)

ABSTRACT

This study examined the variability in frequency of tropical night occurrence (i.e., minimum air temperature >25°C) in Beijing, using a homogenized daily temperature dataset during the period 1960–2008. Our results show that tropical nights occur most frequently in late July and early August, which is consistent with relatively high air humidity associated with the rainy season in Beijing. In addition, year-to-year variation of tropical night occurrence indicates that the tropical nights have appeared much more frequently since 1994, which can be illustrated by the yearly days of tropical nights averaged over two periods: 9.2 days of tropical nights per year during 1994–2008 versus 3.15 days during 1960–1993. These features of tropical night variations suggest a distinction between tropical nights and extreme heat in Beijing.

We further investigated the large-scale circulations associated with the year-to-year variation of tropical night occurrence in July and August, when tropical nights appear most frequently and occupy 95% of the annual sum. After comparing the results in the two reanalysis datasets (NCEP/NCAR and ERA-40) and considering the possible effects of decadal change in the frequency of tropical nights that occurred around 1993/94, we conclude that on the interannual time scale, the cyclonic anomaly with a barotropic structure centered over Beijing is responsible for less frequent tropical nights, and the anticyclonic anomaly is responsible for more frequent occurrence of tropical nights over Beijing.

Key words: tropical night, large-scale circulation, interannual variability, decadal change, Beijing

Citation: Park, J.-K., R. Y. Lu, C. F. Li, and E. B. Kim, 2012: Interannual variation of tropical night frequency in Beijing and associated large-scale circulation background. *Adv. Atmos. Sci.*, **29**(2), 295–306, doi: 10.1007/s00376-011-1141-1.

1. Introduction

High temperature events in summer such as extreme heat and tropical nights greatly affect the human life and social activity. For instance, a high death count was associated with heat waves (among severe weather events such as hurricanes, tornados, floods, lightning, earthquakes) in the United States from 1979 to 1998 (Thornbrugh, 2001). During the summer of 2003, Europe sustained a severe heat wave that resulted in 35 000 heat-related mortalities in many countries: France, Germany, Spain, Italy, England, etc. In the future, high temperature or heat waves may become more intense and longer lasting with climate change (Meehl and Tebaldi, 2004; Park et al., 2008).

High-temperature events can cause heat-related illness and can affect cardiovascular disease and cerebrovascular disease indirectly. When the human body is exposed to high temperature for extended periods, it starts to lose thermoregulatory capability, which is necessary for homeostasis; thus, heatstroke, heat exhaustion, heat syncope and heat cramps can develop (Cinar et al., 2001; Park and Lee, 2006). Many countries are applying and developing the heat/health warning systems to reduce adverse affects of high temperature. Tan et al. (2004) developed a heat/health

*Corresponding author: LU Riyu, lr@mail.iap.ac.cn

warning system in Shanghai, China, using an excess death algorithm.

At a latitude of ∼40°N, Beijing is located at the northern edge of the East Asian summer monsoon region. In mid-July, the western North Pacific subtropical high advances northward and retreats eastward, and the East Asian upper-tropospheric westerly jet shifts northward (Lu, 2001; Lin and Lu, 2008). Concurrent with this change in large-scale circulation, the Meiyu season withdraws in the Huaihe River and Yangtze River basin, and the rainy band shifts northward to North China. Thus, the rainy season appears in late July and early August at Beijing. Prior to the rainy season, the maximum air temperature is generally high. During the rainy season, on the other hand, the southerly flows transfer a large amount of water vapor into North China, and Beijing is frequently humid.

There have been many previously studies on the extreme heat (Zhai and Pan, 2003; Gong et al., 2004; Wei et al., 2004; Jung et al., 2009; Wei and Chen, 2009; Ding et al., 2010; Ding and Qian, 2011; Qian et al., 2011; Sun et al., 2011; Wei and Chen, 2011). In general, these studies, especially recent ones, suggested that extreme heat has increased over most parts of China. In particular, Ding and Qian (2011) suggested that the frequency of wet heat-wave events, which are defined considering both air temperature and relative humidity, were relatively low in the 1980s and increased remarkably since the 1990s. Wei and Chen (2009, 2011) indicated that there is an abrupt increase in the number of days with high temperature around the early 1990s. Wang and Gong (2010) considered both factors of surface air temperature and humidity, and found that "sultry weather" occurred less frequently in the 1990s than in the 1940s. They argued that this phenomenon was due to the "urban dry island" effect induced by the urbanization in Beijing during recent decades. Most of these studies, however, have focused on maximum temperature extreme, and have given less attention to higher minimum temperatures. If minimum air temperature is >25°C (so-called "tropical night"), people over 65 years old are especially vulnerable (Jung et al., 2009). Wei and Sun (2007) revealed that tropical nights may show a different variation with extreme heat.

Weather in Beijing during summer is affected both by the western North Pacific subtropical anticyclone from the south and by mid-latitude disturbances from the north. Therefore, the mechanisms responsible for variability in the frequency of tropical nights in Beijing would be more complicated than those in the monsoonal region in China, where tropical night variability is affected by the monsoonal flows to a larger extent. In addition, as a metropolitan city in China, Beijing has a population of ∼20 million, which is growing at a speed of 0.5 million per year. This dense and large population requires better understanding and forecasting of the tropical night variability.

In this study, we first investigated the subseasonal and interannual variability in tropical night frequency in Beijing, and we made a brief comparison with variability in extreme heat (section 3). Then we examined the large-scale atmospheric circulations associated with the interannual variation of tropical night occurrence (section 4). The conclusion is given in the final section (section 5).

2. Data and methods

Temperature data used in this study were the Homogenized Daily Mean/Maximum/Minimum Temperature Series from 549 National Standard Stations in China during the period 1960–2008, a dataset provided by Li and Yan (2009, 2010). This dataset has been used in several previous studies on temperature extremes (e.g., Ding and Qian, 2011; Wei and Chen, 2011).

Tropical nights were defined simply by the criterion that the minimum air temperature >25°C. This definition is the same as that used by Wei and Sun (2007). Extreme heat days were defined as an occurrence of daily maximum temperature above the 95th percentile of the daily maximum temperature distribution during the study period, which was 33.2°C for Beijing. This value was lower than the criterion (35.0°C) for extreme heat days widely used for the whole mainland China, partially because air temperature in Beijing is generally lower than that in South and Central China.

Circulation data used in this study were from both the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis data from 1960 to 2002 (Uppala et al., 2005) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from 1960 to 2008 (Kalnay et al., 1996).

3. Subseasonal and interannual variability in tropical night

Figure 1 shows the daily occurrence frequency of tropical night and extreme heat at Beijing from May to September, averaged over 49 years from 1960 to 2008. The tropical nights are clearly concentrated in July and August, while there is only 1 day of tropical night in May and 11 days in June, and there is no day of tropical night in September during the entire analysis period 1960–2008 (Fig. 1a; Table 1). There

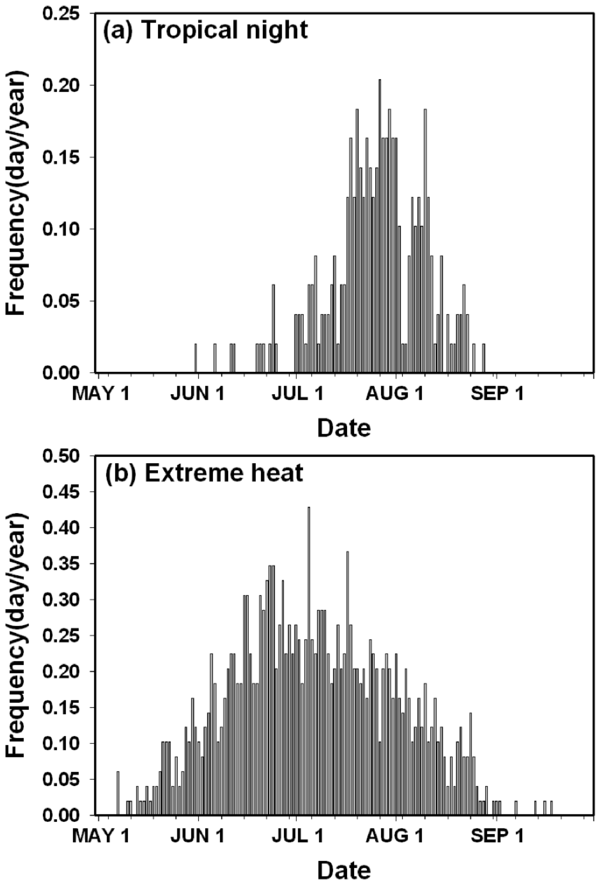

Fig. 1. Frequency of (a) tropical nights and (b) extreme heat days at Beijing from May to September, averaged over 49 years from 1960 to 2008. Units: d yr^{-1}.

is a sharp increase in tropical night frequency after 17 July and a decrease after 10 August. This period of frequent occurrence of tropical nights is consistent with the rainy season in Beijing. On the other hand, the days of extreme heat increase after early May and reach a peak in late June (Fig. 1b). After the peak, the days of extreme heat fluctuate for ∼1 month, and decrease after late July. In September, there are only 6 days of extreme heat in the total 49 years (Table 1).

Figure 1 indicates that the subseasonal variation in tropical nights differs remarkably to that in extreme heat. The frequency of extreme heat days reaches its peak much earlier than the tropical night frequency, and begins to decrease clearly after the tropical night occurrence reaches its peak on ∼20 July. This is consistent with the subseasonal change in humidity at Beijing: Humidity is relatively low before middle July and increases afterward, in concurrence with the beginning of rainy season in Beijing. The consistency between the subseasonal changes in tropical night occurrence and humidity suggests that the change in air humidity may influence tropical night variability in Beijing, where the subseasonal change in air humidity is much greater than that in Central and South China during summer.

Figure 2 shows the monthly occurrence of tropical nights and extreme heat at Beijing from May to September in each year from 1960 to 2008. The occurrence of tropical nights has significantly increased after 1994 (Fig. 2a). Tropical nights occurred every year after 1994, while there were 5 years of no tropical nights before this year. The frequency of tropical

Table 1. Monthly occurrence of tropical nights ($T_{\min} > 25.0°C$) and extreme heat ($T_{\max} > 33.2°C$) days at Beijing during 49 years from 1960 to 2008. Units: d.

	May	Jun	Jul	Aug	Sep
Tropical night	1	11	151	82	0
Extreme heat	70	323	351	157	6

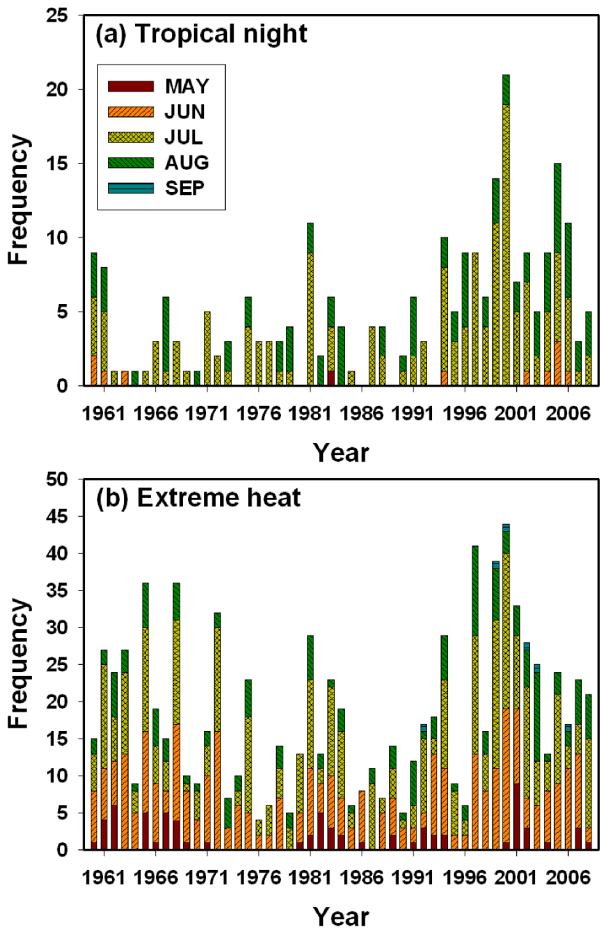

Fig. 2. Interannual variation of monthly (from May to September) occurrence of (a) tropical nights and (b) extreme heat days at Beijing during 1960–2008. Units: d.

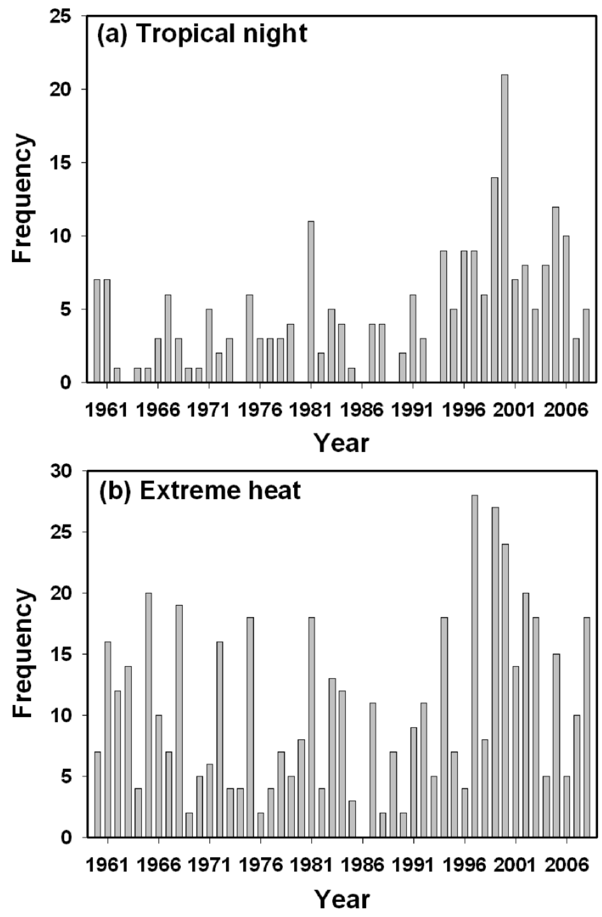

Fig. 3. Interannual variation of frequency of (a) tropical nights and (b) extreme heat days at Beijing in July and August. Units: d.

nights averaged over the years of 1994–2008 is 9.2 days per year, while that averaged over 1960–1993 is 3.15 days per year. The frequency of tropical nights during the later period is almost three times as larger as that during the former period. The highest number of tropical nights occurred in the year 2000. In this year, there were 19 days of tropical night in July, the only month during the entire analysis period in which tropical night frequency was >50%. Most tropical nights appear in July and August, in agreement with the result shown in Fig. 1a. This is true both before and after 1993/94.

The variation of extreme heat days differs considerably from that of tropical nights. The extreme heat occurrence (Fig. 2b) did not exhibit an increase around 1993/94 as clearly as the tropical night occurrence. The extreme heat days tended to occur frequently in 1960s and after the mid-1990s, with a period of fewer days from the 1970s to the mid-1990s, which is basically consistent with the report of Wei and Sun (2007).

During the entire analysis period, there were 233 days of tropical nights in July and August (Table 1), comprising 95% of tropical nights across the whole year. Therefore, in the following analyses, we focused on the tropical night variability in these 2 months. Figure 3 shows the total occurrence of tropical nights and extreme heat days at Beijing in July and August of each year. Consistent with the result shown in Fig. 2a, July–August tropical nights appeared more frequently after 1994, while they occurred less frequently before 1993. The frequency of tropical nights in July and August averaged over the years of 1994–2008 is 8.73 days per year, while that averaged over the years of 1960–1993 is 3.0 days per year. The variation of extreme heat days in July and August (Fig. 3b) is roughly similar to that of yearly extreme heat days shown in Fig. 2b, although the extreme heat days in Fig. 3 are fewer without the contribution from June.

4. Large-scale circulation background for tropical nights

4.1 *Composite analysis using the NCEP/NCAR reanalysis and ERA-40 reanalysis*

Surface air temperatures are determined by many factors, such as atmospheric circulation, cloud cover, surface conditions, and so on. In this study, we focused on the large-scale circulation associated with the tropical nights at Beijing, that is, the large-scale circulation that can provide a background favorable for the occurrence of the tropical nights. Other factors, as well as the features of atmospheric circulation associated with the tropical nights on the synoptic scale, are left to the future studies.

Figure 4 shows the upper- and lower-tropospheric circulations associated with the frequent occurrence of tropical nights in July and August. The years of frequent tropical nights were defined as are those with more than seven tropical nights in July and August. To facilitate the comparison, the circulations averaged over the years when there was no or only one tropical night in July and August are also given. For brevity, these years are called "tropical-night years" and "no-tropical-night years," respectively. The tropical-night years include 1981, 1994, 1996, 1997, 1999, 2000, 2002, 2004, 2005 and 2006 (10 years), and the no-tropical-night years are 1962, 1963, 1964, 1965, 1969, 1970, 1974, 1980, 1985, 1986, 1989 and 1993 (12 years). All of the no-tropical-night years appear before the changing point 1993/94, and all the tropical-night years, except 1981, appear after the changing point, consistent with the clear decadal change in tropical night occurrence around 1993/94. Therefore, the differences in circulation between the tropical-night years and no-tropical-night years may be affected by the decadal

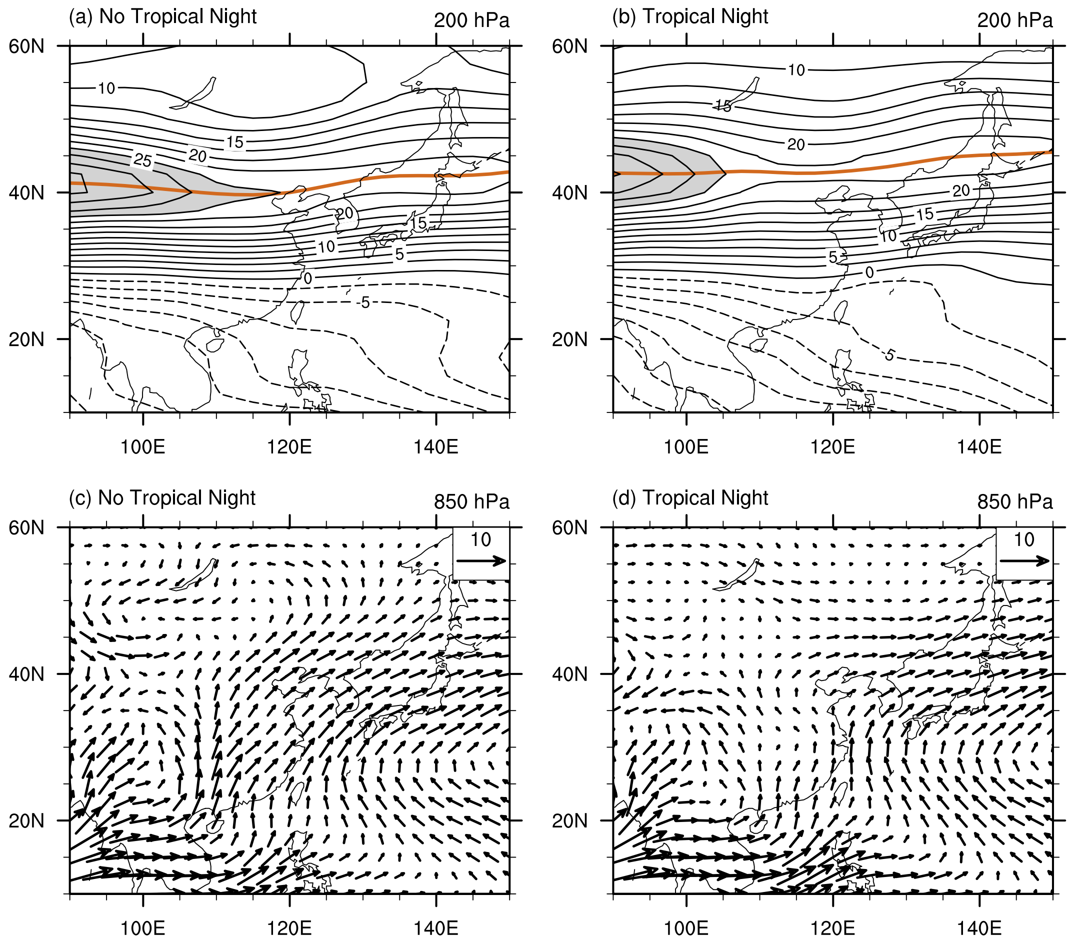

Fig. 4. Composite July–August mean 200-hPa zonal wind (upper panels) and 850-hPa horizontal winds (lower panels) for the no-tropical-night years (left column) and tropical-night years (right column). The NCEP/NCAR reanalysis data during 1960–2008 are used. The color lines indicate the location of the westerly jet axis in panels (a) and (b).

change around 1993/94. Kwon et al. (2007) found that the upper-tropospheric subtropical westerly jet has weakened significantly over northern China since 1994. They explained this decadal change in zonal winds as a barotropic response to a steady forcing from increased precipitation in South China. The possible effects of this decadal change on our results are discussed in the following subsection.

Figures 4a and b indicate that the upper-tropospheric westerly jet stream in the mid-latitudes shifts northward and weakens over the northeastern Asia for the years of frequent tropical nights, compared with the years of no tropical nights. This weakening of the jet can be judged by the location of the contour line of 25 m s^{-1}: it extends eastwards into North China during the no-tropical-night years but remains over Northwest China during the tropical-night years. Furthermore, the jet axis exhibits a curve over the northeastern Asia during the no-tropical-night years but appears almost as a straight line during the tropical-night years. This difference in shape of the jet axis is associated with the spatial distribution of the horizontal winds: There is a trough at the upper troposphere over northeastern Asia during the years of no tropical night, but this trough is almost undetectable and thus the horizontal winds tend to be zonally oriented during the years of tropical nights (not shown). The lower-tropospheric circulations also show a clear difference between the years of tropical nights and no tropical nights (Figs. 4c and d). For the no-tropical-night years, southwesterlies dominate over East Asia. For the tropical-night years, a ridge appears clearly over North China, including Beijing.

The differences in circulation between the tropical-night and no-tropical-night years can be more clearly illustrated by Fig. 5, which shows the wind anomalies at the upper and lower troposphere, respectively. The composite upper-tropospheric wind anomalies for the

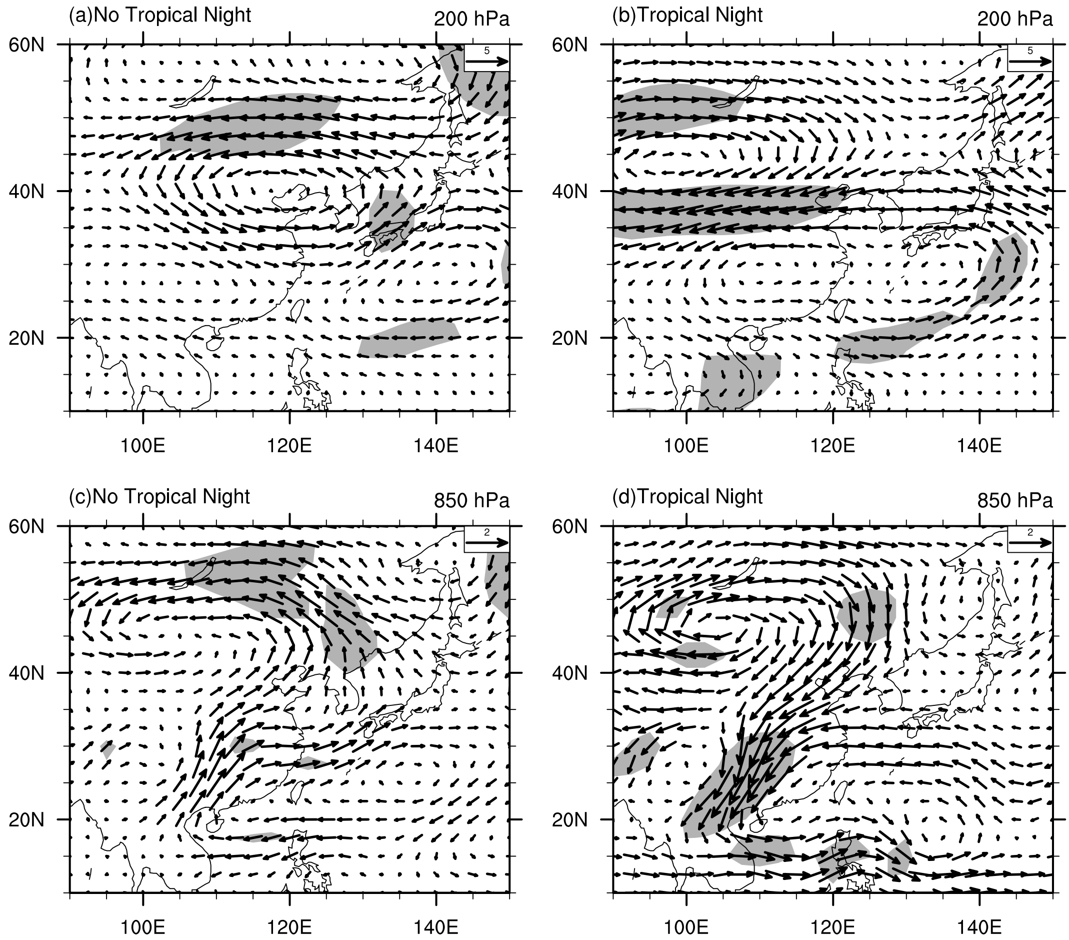

Fig. 5. Same as Fig. 4, but for anomalies. The shading indicates that either zonal or meridional wind anomalies are significant at the 95% level according to the Student's *t*-test.

no-tropical-night years are characterized by an anomalous cyclone over East Asia, with Beijing locating at the center of this cyclonic anomaly (Fig. 5a). For the tropical-night years, however, there is an anticyclonic anomaly at the upper troposphere over Mongolia (Fig. 5b). The anomalous patterns exhibit a clear difference between the no-tropical-night years and tropical-night years: the upper-tropospheric anticyclonic anomaly located southwest of Beijing for the tropical-night years, while the cyclonic anomaly centered at Beijing for the no-tropical-night years. This difference in the anomalous patterns is discussed further in the following subsection.

In the lower troposphere, the circulation anomalies associated with no tropical nights and tropical nights share essentially similar spatial patterns but with different signs (Figs. 5c and d). There is a cyclonic anomaly over Mongolia, an anticyclonic anomaly over the subtropical western North Pacific, and a southwesterly anomaly over North China for the no-tropical-night years. There is an anticyclonic anomaly over Mongolia, a cyclonic anomaly over the subtropical western North Pacific, and a northeasterly anomaly over North China for the tropical-night years. However, previous studies have documented that the NCEP/NCAR reanalysis data have some problems in the lower troposphere over the Eurasian continent prior to 1979 and thus show an artificial interdecadal change in the lower-tropospheric circulations (Yang et al., 2002; Inoue and Matsumoto, 2004; Wu et al., 2005; Huang, 2006). Due to the existence of a clear decadal variation in the tropical nights, i.e., the significant increase of tropical nights since 1994, the results shown in Figs. 4 and 5 may have been affected by the artificial interdecadal change in the NCEP/NCAR reanalysis data.

Therefore, the ERA-40 reanalysis data were used to repeat the above analysis. Figure 6 shows the composite winds for the no-tropical-night and tropical-night years, respectively, using the ERA-40 reanalysis data. The results for upper-tropospheric winds are almost identical to those obtained by the NCEP/NCAR re-

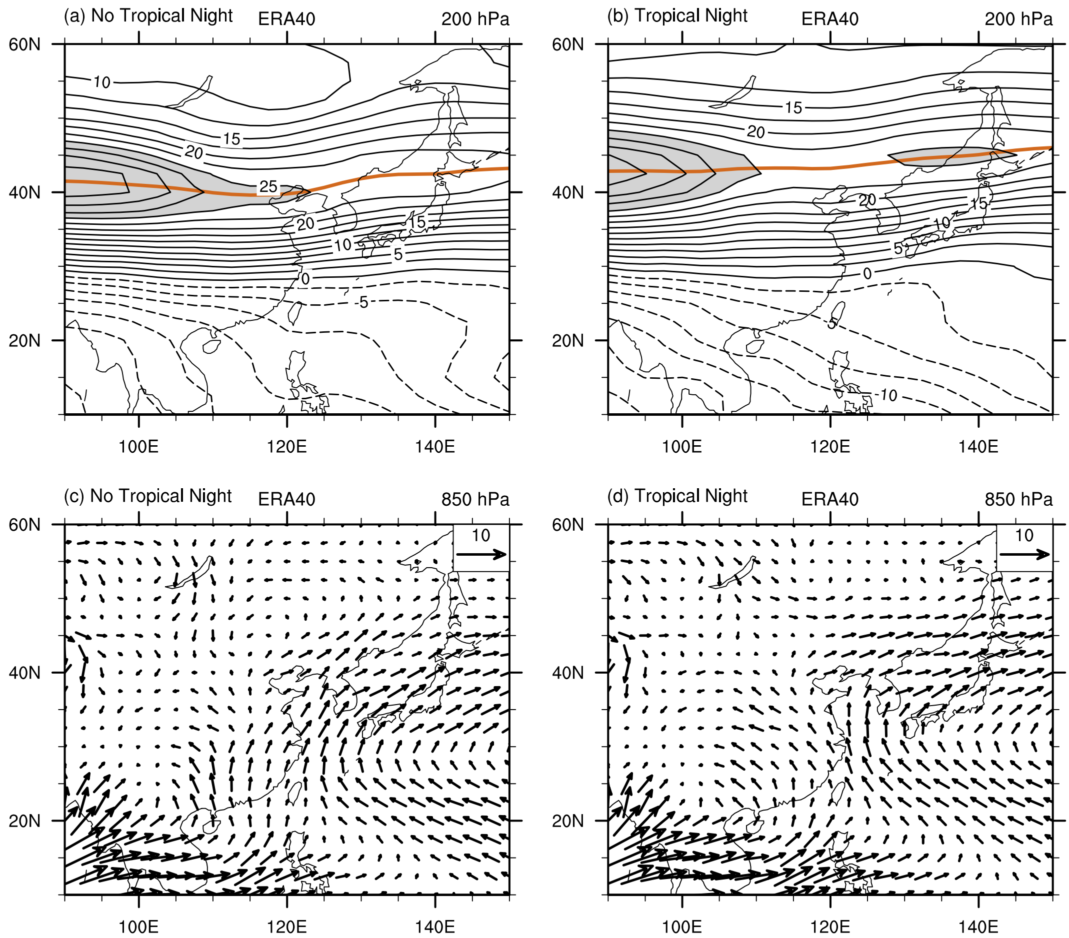

Fig. 6. Same as Fig. 4, but using the ERA-40 reanalysis data during 1960–2002.

analysis data. This is in agreement with previous results, which showed that the artificial interdecadal change in the NCEP/NCAR reanalysis data is basically concentrated in the lower troposphere (Yang et al., 2002; Inoue and Matsumoto, 2004; Wu et al., 2005; Huang, 2006). The lower-tropospheric circulations, accordingly, show a somewhat different result using these two datasets. For the no-tropical-night years, southwesterlies still dominate over East Asia, but they are much weaker than those shown using the NCEP/NCAR reanalysis data. For the tropical-night years, there is also a ridge over North China, although it is slightly weaker in comparison with the result by the NCEP/NCAR reanalysis data.

Figure 7 shows the composite wind anomalies using the ERA-40 reanalysis data. Again, the results for upper troposphere are almost identical to those obtained using the NCEP/NCAR reanalysis data. In the lower troposphere, there is a cyclonic anomaly over North China, and an anticyclonic anomaly over the subtropical western North Pacific for the no-tropical-night years; there is an anticyclonic anomaly over North China, and a cyclonic anomaly over the subtropical western North Pacific for the tropical-night years. These wind anomalies are significantly different from those using the NCEP/NCAR reanalysis data (Figs. 5c and 5d), particularly over the mid-latitudes. The cyclonic (anticyclonic) anomaly is located northwest to Beijing in the NCEP/NCAR reanalysis results, but is basically centered at Beijing in the ERA-40 reanalysis results. In addition, the strong southwesterly (northeasterly) anomaly over North China in the NCEP/NCAR reanalysis does not appear in the ERA-40 reanalysis. These differences in the lower-tropospheric winds between the two datasets indicate that the aforementioned results using the NCEP/NCAR reanalysis are indeed affected by the artificial interdecadal change, and the ERA-40 reanalysis results are more reliable, despite the slightly shorter length of data in this reanalysis dataset. Figures 7c and d suggest that the cyclonic anomaly centered over Beijing is responsible for the less frequent tropical nights and that the anticyclonic anomaly is responsible for more frequent tropical nights.

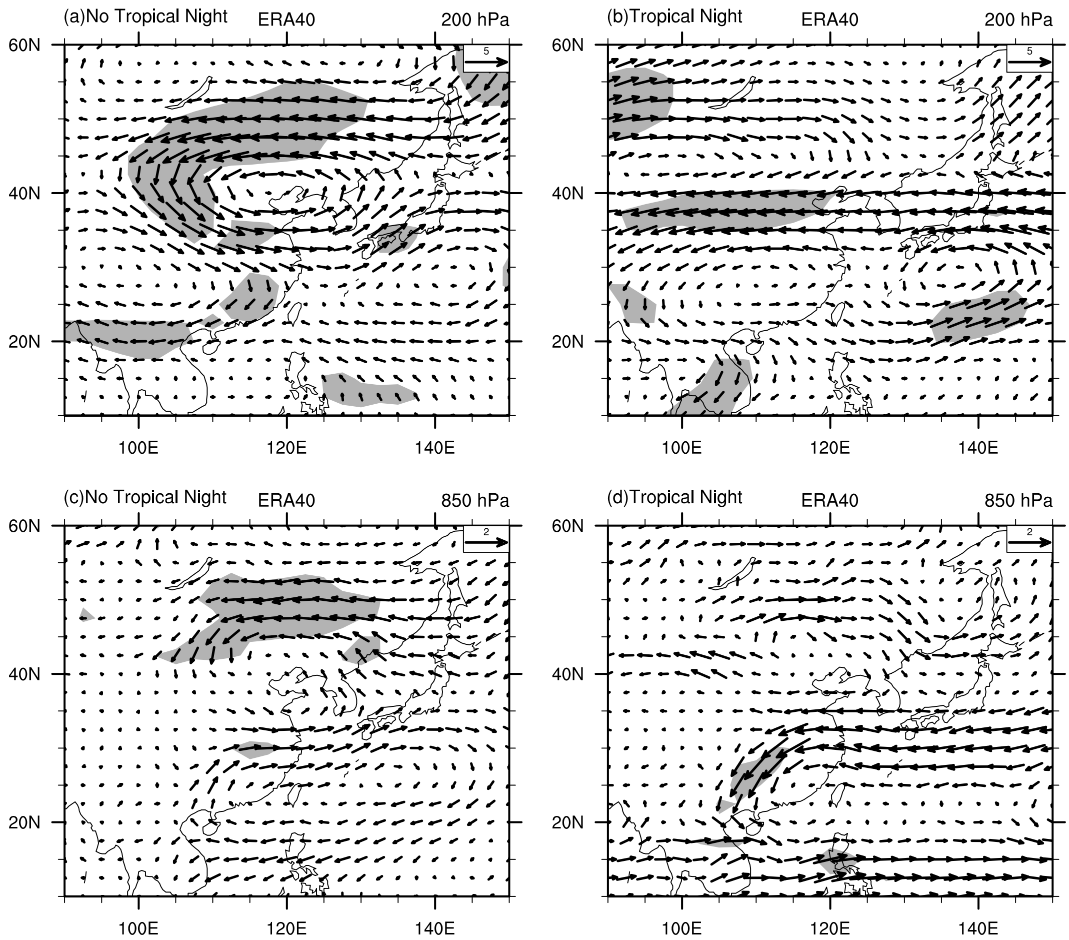

Fig. 7. Same as Fig. 5, but using the ERA-40 reanalysis data during 1960–2002.

4.2 *Effects of the decadal change around* 1993/94

There has been a clear increase in tropical nights since 1994. So, a question arises: Is this increase due to the global warming trend or to a natural decadal change? As the first approximation, we assume that the former induces circulation anomalies on the global scale, but the latter is related to local circulation anomalies.

Figure 8 shows the difference in horizontal winds between the periods before and after 1993/94, that is, the average over 1994–2002 minus the average over 1979–1993, using the ERA-40 reanalysis data. In the upper troposphere, there is an anticyclonic anomaly northwest to Beijing and a cyclonic anomaly southeast to this anticyclonic anomaly. Associated with both the anticyclonic and cyclonic anomalies, there is a strong easterly anomaly along 40°N, which indicates a significantly weakened upper-tropospheric westerly jet stream. These results are consistent with Kwon et al. (2007). In the lower troposphere, there is an anticyclonic anomaly centered roughly over Beijing. This lower-tropospheric anticyclonic anomaly is obscure and tends to locate southeastward in comparison with its upper-tropospheric counterpart. These decadal changes in atmospheric circulation tend to be a local phenomenon, implying that they are essentially related to natural change, rather than global warming. Kwon et al. (2007) suggested that the decadal change in the upper-tropospheric circulation that occurred around 1993/94 is due to the rainfall increase in South China.

The composite results shown in the preceding subsection may be affected by the decadal change shown in Fig. 8, due to the clear increase in the occurrence of tropical nights since 1994. Therefore, we repeated the analyses outlined in the preceding subsection using the data from 1960 to 1993, to remove the decadal change and to focus on interannual variability. For brevity, we have shown only the results from the ERA-40 reanalysis data. The results from the NCEP/NCAR reanalysis (not shown) are significantly affected by the artificial decadal changes over the Eurasian continent

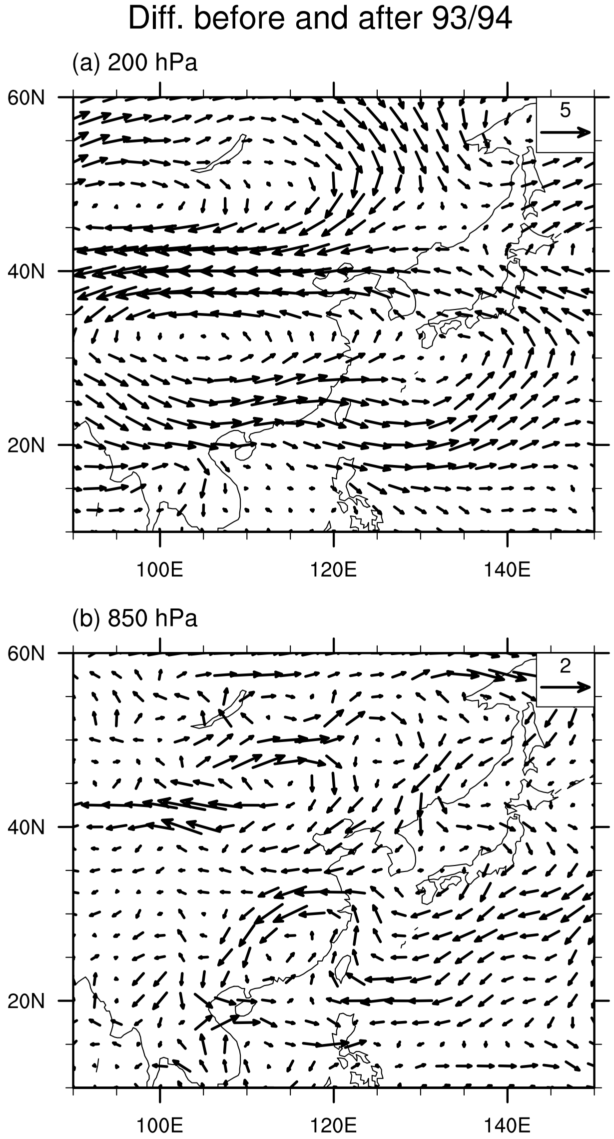

Fig. 8. Difference in horizontal winds between the periods before and after 1993/94, that is, the average over 1994–2002 minus the average over 1979–1993, at (a) 200 hPa and (b) 850 hPa. The ERA-40 reanalysis data are used.

in the lower troposphere, but they are almost identical to the ERA-40 results in the upper troposphere.

Figure 9 shows the composite winds for the tropical-night years and no-tropical-night years, respectively, for the period 1960–1993, calculated using the ERA-40 reanalysis data. In the upper troposphere, for the tropical-night years, the westerly jet stream is extended further northward, and the curve of the jet axis that appears for the no-tropical-night years over the northeastern Asia is not detectable. These results are similar to the results shown in Figs. 4 and 6, confirming that the northward extended westerly jet and the zonally oriented jet axis are favorable for tropical night frequency. This conclusion is not affected by the significant decadal change in the upper troposphere around 1993/94. In the lower troposphere, the ridge over North China for the tropical-night years is much weaker in comparison with that shown in Fig. 6d, likely associated with the less frequent occurrence of tropical nights during the period 1960–1993.

Notably, the tropical-night years differ from those in the preceding subsection. There was only 1 year of frequent tropical nights (i.e., 1981) during the period 1960–1993 according to the criterion applied in the preceding subsection. Thus, in this subsection we modify the criterion as: the years with >4 tropical nights in July and August. The tropical-night years according to the new criterion include 1960, 1961, 1967, 1971, 1975, 1981, 1983 and 1991 (8 years). The years with no tropical nights remain the same.

Figure 10 shows the composite wind anomalies by using the ERA-40 reanalysis data during the period 1960–1993. The most striking difference with the results shown in Figs. 5 and 7 is the location of upper-tropospheric anticyclonic anomaly for the tropical-night years. This anticyclonic anomaly shifts significantly southeastward, and centered roughly over Beijing (Fig. 10b). Due to this southward shift of the anticyclonic anomaly for the tropical-night years, the circulation anomalies over the mid-latitudes in Asia exhibit antisymmetry between the tropical-night years and no-tropical-night years: cyclonic anomaly for no tropical night and anticyclonic anomaly for tropical nights, both roughly centered over Beijing. The lower-tropospheric circulation anomalies (Figs. 10c and d), on the other hand, are similar to those in Figs. 7c and d, although the cyclonic anomaly over the subtropical western North Pacific for the tropical-night years is relatively weaker. Figure 10 indicates that the circulation anomalies for both no-tropical-night years and tropical-night years exhibit a barotropic structure. Therefore, it can be concluded that the barotropic cyclonic anomalies centered over Beijing are responsible for less frequent tropical nights and anticyclonic anomalies are responsible for more frequent tropical nights over Beijing.

5. Conclusions and discussion

In this study, we examined the seasonal and interannual variability in frequency of tropical nights during the period 1960–2008 in Beijing, the capital city of China, using the homogenized daily mean/maximum–minimum temperature series dataset prepared by Li and Yan (2009, 2010). In addition, we investigated the large-scale atmospheric circulations associated with

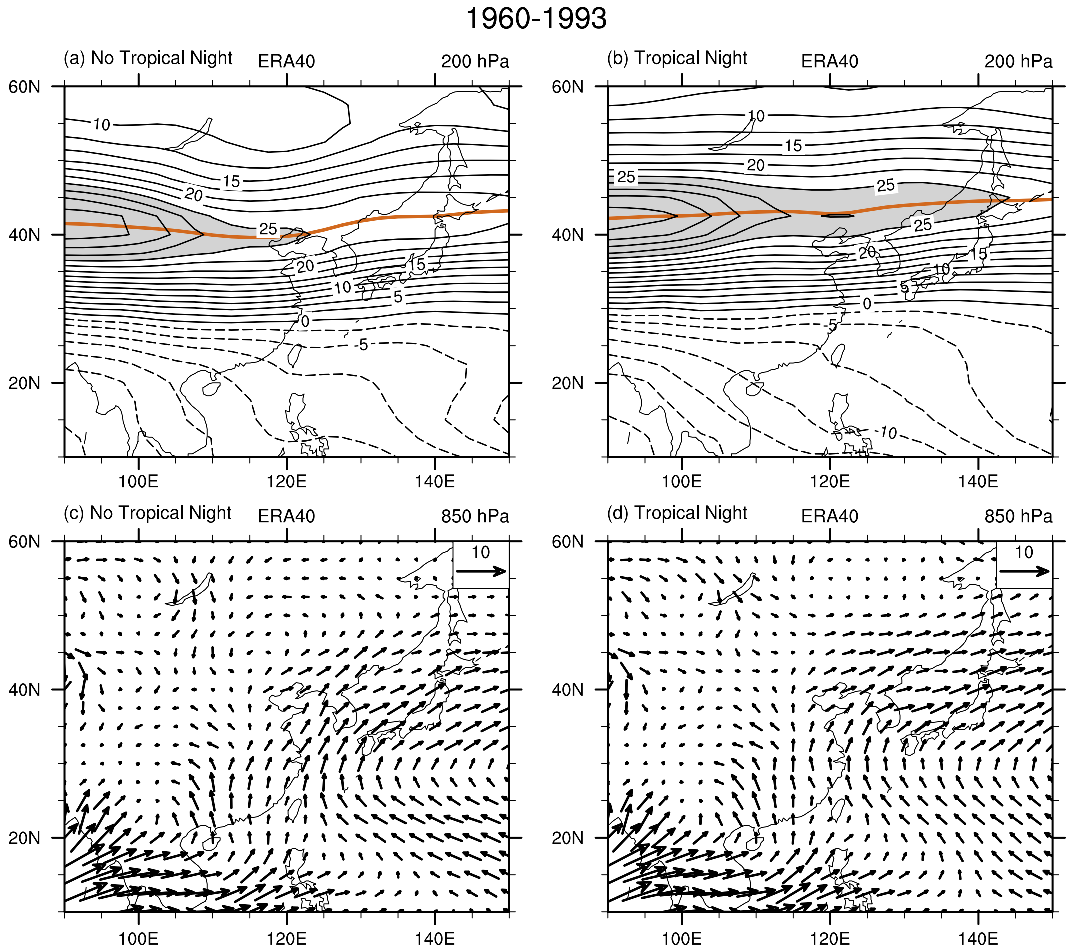

Fig. 9. Same as Fig. 4, but using the ERA-40 reanalysis data during 1960–1993.

the interannual variation of tropical night frequency in Beijing, using both the NCEP/NCAR and ERA-40 reanalysis datasets.

Our results show that, climatologically, tropical nights occur most frequently in late July and early August, which is consistent with relatively high humidity associated with the rainy season in Beijing. On the other hand, days of extreme heat appear most frequently prior to the rainy season in Beijing, suggesting a distinction between subseasonal variations of tropical nights and extreme heat days. Tropical nights have occurred much more frequently since 1994, in comparison with the prior period. There were 9.2 tropical nights per year during 1994–2008, but only 3.15 during 1960–1993. The frequency of tropical nights during the later period is almost three times larger than that during the former period.

Because the days of tropical night in July and August occupy 95% of annual tropical nights, we focused on these 2 months to investigate the large-scale circulations associated with the year-to-year variation of tropical night occurrence. The July–August tropical nights also appeared more frequently after 1994. This decadal change in tropical nights concurs with the decadal change in the upper-tropospheric westerly jet over North China (Kwon et al., 2007), although the mechanism for the relationship between tropical nights in Beijing and the westerly jet over North China is still unknown. Composite analyses based on the interannual variation of tropical night frequency indicate that the cyclonic anomalies with a barotropic structure and centered over Beijing are responsible for the less frequent occurrence of tropical nights, while anticyclonic anomalies are responsible for greater frequency of tropical nights over Beijing.

Notably, some of the circulation anomalies in the present results are not statistically significant. This is due to the fact that tropical nights are closely related to weather phenomenon, and they occur during a small potion of the summer period. The largest number of tropical nights in July and August during the entire analysis period was 21, which appeared in 2000, and this number is only about one-third of days in July and August. However, the well-organized patterns of cir-

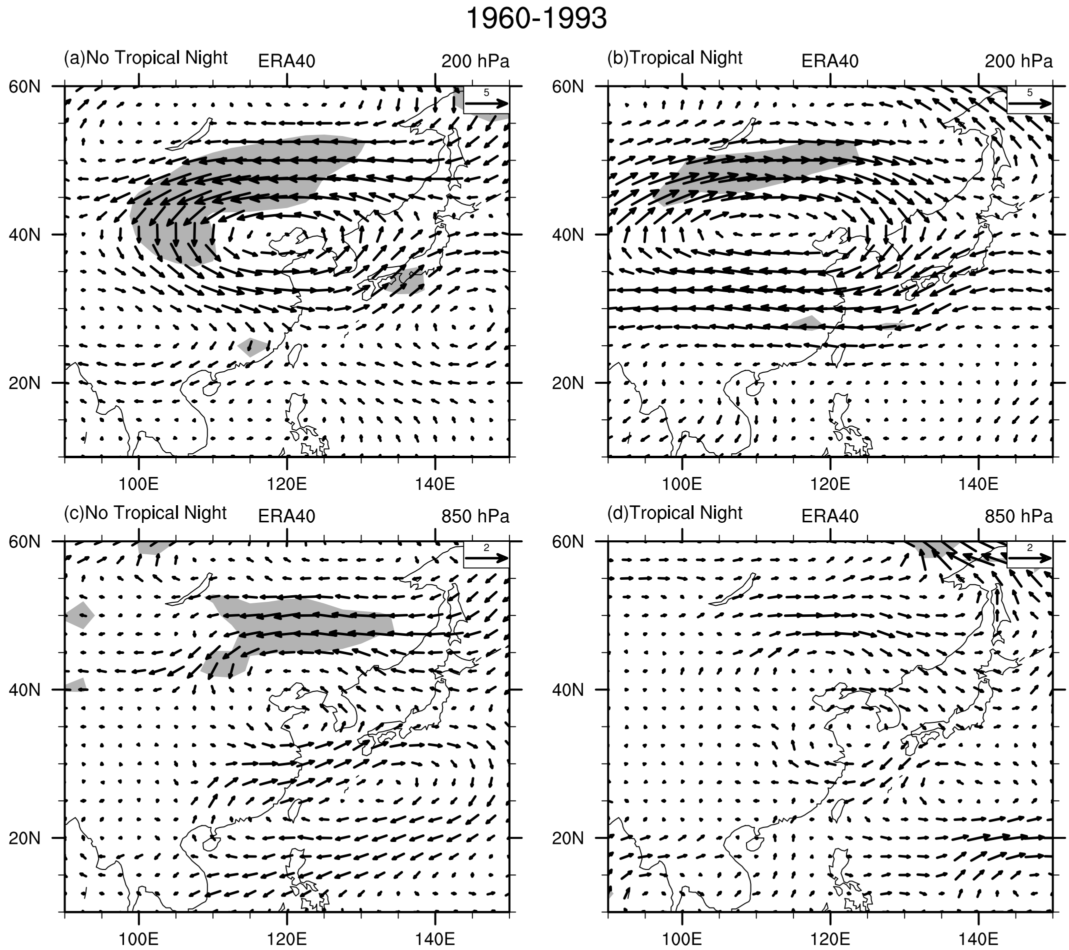

Fig. 10. Same as Fig. 5, but using the ERA-40 reanalysis data during 1960–1993.

culation anomalies in these results suggest that year-to-year variation of July–August circulations may provide a favorable or unfavorable background condition for frequent occurrence of tropical nights. This conclusion should be confirmed by further analyses on both seasonal and synoptic time scales, which are ongoing.

Acknowledgements. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST; Grant No. 2010-0028715).

REFERENCES

Cinar, Y., A. M. Senyol, and K. Duman, 2001: Blood viscosity and blood pressure: Role of temperature and hyperglycemia. *American Journal of Hypertension*, **14**, 433–438.

Ding, T., and W. Qian, 2011: Geographical patterns and temporal variations of regional dry and wet heatwave events in China during 1961–2008. *Adv. Atmos. Sci.*, **28**, 322–337, doi: 10.1007/s00376-010-9236-7.

Ding, T., W. Qian, and Z. Yan, 2010: Changes in hot days and heat waves in China during 1961–2007. *Int. J. Climatol.*, **30**, 1452–1462.

Gong, D. Y., Y. Z. Pan, and J. A. Wang, 2004: Changes in extreme daily mean temperatures in summer in eastern China during 1955–2000. *Theor. Appl. Climatol.*, **77**, 25–37.

Huang, G., 2006: The assessment and difference of the interdecadal variations of climate change in northern part of China with the NCEP/NCAR and ERA-40 reanalysis data. *Climatic and Environmental Research*, **11**, 310–320. (in Chinese)

Inoue, T., and J. Matsumoto, 2004: A comparison of summer sea level pressure over east Eurasia between NCEP–NCAR reanalysis and ERA-40 for the period of 1960–99. *J. Meteor. Soc. Japan*, **82**, 951–958.

Jung, W. S., J. K. Park, U. B. Kim, and J. H. Song, 2009: Study on the establishment of threshold criteria for heat health watch warning system in Korea. Part II: Improvement of criteria. *Journal of the Environmental Sciences*, **18**, 781–796. (in Korean)

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kwon, M., J.-G. Jhun, and K.-J. Ha, 2007: Decadal change in East Asian summer monsoon circulation in the mid-1990s. *Geophys. Res. Lett.*, **34**, L21706, doi: 10.1029/2007GL031977.

Li, Z., and Z. W. Yan, 2009: Homogenized daily mean/maximum/minimum temperature series for China from 1960–2008. *Atmos. Oceanic Sci. Lett.*, **2**, 237–243.

Li, Z., and Z. W. Yan, 2010: Application of multiple analysis of series for homogenization to Beijing daily temperature series (1960–2008). *Adv. Atmos. Sci.*, **27**, 777–787, doi: 0.1007/s00376-009-9052-0.

Lin, Z., and R. Lu, 2008: Abrupt northward jump of the East Asian upper-tropospheric jet stream in midsummer. *J. Meteor. Soc. Japan*, **84**, 857–866.

Lu, R.-Y., 2001: Interannual variability of the summertime North Pacific subtropical high and its relation to atmospheric convection over the Warm Pool. *J. Meteor. Soc. Japan*, **79**, 771–783.

Meehl, G. A., and C. Tebaldi, 2004: More intense, more frequent and longer heat waves in the 21st century. *Science*, **305**, 994–997.

Park, J. K., and D. G. Lee, 2006: Correlation between daily mortality and temperature of Seoul, in summer. *Proc. 99th Annual Meeting of AWMA*, New Orleans, LA., Paper No. 06-A-384-AWMA.

Park, J. K., W. S. Jung, and U. B. Kim, 2008: A study on development of the extreme heat standard in Korea. *Journal of the Environmental Sciences*, **17**, 657–669. (in Korean)

Qian, C., Z. Yan, Z. Wu, C. Fu, and K. Tu, 2011: Trends in temperature extremes in association with weather-intraseasonal fluctuations in eastern China. *Adv. Atmos. Sci.*, **28**, 297–309, doi: 10.1007/s00376-010-9242-9.

Sun, Q., H. Wang, and W. Yuan, 2011: Decadal variability of the extreme hot event in China and its association with atmospheric circulations. *Climatic and Environmental Research*, **16**, 199–208. (in Chinese)

Tan, J., L. S. Kalkstein, J. Huang, S. Lin, H. Yin, and D. Shao, 2004: An operational heat/health warning system in Shanghai. *International Journal of Biometeorology,* **48**, 157–162.

Thornburgh, C., 2001: Are America's cities ready for the hot times ahead? SOARS summer 2001 Program, 1–14.

Uppala, S. M., and Coauthors, 2005: The ERA-40 reanalysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.

Wang, X. Q., and Y. B. Gong, 2010: The impact of an urban dry island on the summer heat wave and sultry weather in Beijing City. *Chinese Sci. Bull.*, **55**, 1657–1661, doi: 10.1007/s11434-010-3088-5.

Wei, J., and J. Sun, 2007: The analysis of summer heat wave and sultry weather in North China. *Climatic and Environmental Research*, **12**, 453–463. (in Chinese)

Wei, K., and W. Chen, 2009: Climatology and trend of high temperature extremes across China in summer. *Atmos. Oceanic Sci. Lett.*, **2**, 153–158.

Wei, K., and W. Chen, 2011: An abrupt increase in the summer high temperature extreme days across China in the mid-1990s. *Adv. Atmos. Sci.*, **28**(5), 1023–1029, doi: 10.1007/s00376-010-0080-6.

Wei, J., H. Yang, and S. Sun, 2004: Relationship between the anomaly longitudinal position of subtropical high in the western Pacific and severe hot weather in North China in summer. *Acta Meteorologica Sinica*, **62**, 308–316. (in Chinese)

Wu, R., J. L. Kinter, and B. P. Kirtman, 2005: Discrepancy of interdecadal changes in the Asian region among the NCEP–NCAR reanalysis, objective analyses, and observations. *J. Climate*, **18**, 3048–3067.

Yang, S., K. M. Lau, K. M. Kim, 2002: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.

Zhai, P., and X. Pan, 2003: Trends in temperature extremes during 1951–1999 in China. *Geophys. Res. Lett.*, **30**, 1913, doi: 10.1029/2003GL018004.