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Characteristics of the Heat Island Effect in Shanghai and Its Possible Mechanism

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ABSTRACT

The characteristics of the urban heat island effect and the climate change in Shanghai and its possible mechanism are analyzed based on monthly meteorological data from 1961 to 1997 at 16 stations in Shanghai and its adjacent areas. The results indicate that Shanghai City has the characteristics of a heat island of air temperature and maximum and minimum air temperature, a cold island of surface soil temperature, a weak rainy island of precipitation, and a turbid island of minimum visibility and aerosols, with centers at or near Longhua station (the urban station of Shanghai). Besides theses, the characteristics of a cloudy island and sunshine duration island are also obvious, but their centers are located in the southern part of the urban area and in the southern suburbs. A linear trend analysis suggests that all of the above urban effects intensified from 1961 to 1997. So far as the heat island effect is concerned, the heat island index (difference of annual temperature between Longhua and Songjiang stations) strengthens (weakens) as the economic development increases (decreases). The authors suggest that the heating increase caused by increasing energy consumption due to economic development is a main factor in controlling the climate change of Shanghai besides natural factors. On the other hand, increasing pollution aerosols contribute to the enhancement of the turbid island and cooling. On the whole, the heating effect caused by increasing energy consumption is stronger than the cooling effect caused by the turbid island and pollution aerosols.

Key words: Shanghai heat island, climate change due to economic development, cooling effect due to clouds and aerosols, rainy island, turbid island

1. Introduction

Scientists generally agree that the climate has been warming up since the 19th century (IPCC, 2001), and many trend curves of observed datasets include the effect of an urban heat island at present. Yet many scientists (e.g., Jones et al., 1990; Peterson et al., 1999) have compared the city temperature with rural temperature, and have suggested that the effect of an urban heat island is one order less than the global warming of the air temperature. However, the heat island effect is large for local climate change. For example, during 1901–1984 in North America, the difference in temperature between a city with a population near 100 000 and its adjacent rural area is nearly 0.1°C $(10\,\text{yr})^{-1}$ (Karl, 1988). Although the amount of a city with a population over 100 000 is not too much, its urban heat island effect should be considered. In other words, the change of the urban heat island for a big city may cause the climate anomaly (Oke, 1984).

The Changjiang Delta has become a regional heat island due to the rapid development of the economy (Chen et al., 2000). Shanghai City is one of the most flourishing areas in the economy of China, and is an important central city of the heat island in the Changjiang Delta. In this field, Zhou et al. (1988), Zhou and Wu (1987), and Zhou (1991) studied the effect of the urban island in Shanghai and pointed out that it is rather obvious that the effect of the urban heat island in Shanghai City has been caused by the rapid development of the economy. Besides, Zhou and Shu (1994), and Yan and Xu (1996) suggested that Shanghai has the notable features of a hot, rainy, and turbid island. Ding et al. (2002) and Ding and Ye (2002) studied the distribution of high temperature and the heat island effect in midsummer and indicated that the temperature difference between Longhua (ur-

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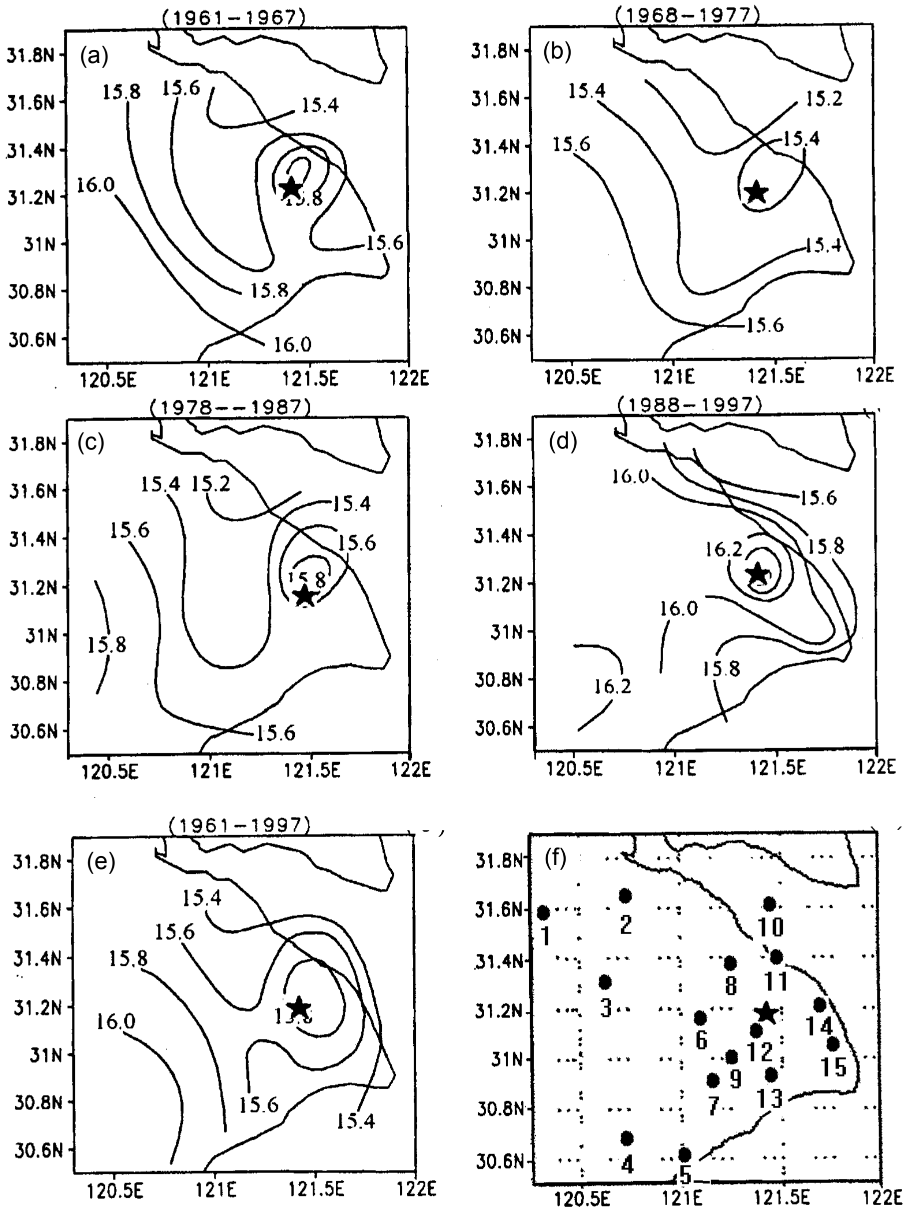

Fig. 1. Annual air temperature around Shanghai and its decadal change. (a) 1961–1967; (b) 1968–1977; (c) 1978–1987; (d) 1988–1997; (e) 1961–1997 (units: °C); (f) distribution of stations. 1: Wuxi; 2: Changshu; 3: Suzhou; 4: Jiaxing; 5: Pinghu; 6: Qingpu; 7: Jinshan; 8: Jiading; 9: Songjiang; 10: Chongming; 11: Baoshan; 12: Minhang; 13: Fengxian; 14: Chuansha; 15: Nanhui. ⋆: Longhua station (in the urban district of Shanghai).

ban station) and Chongming (suburban station) increased rapidly after 1975. Especially in summer, it increased 0.7°C during the last twenty years. Furthermore, Deng et al. (2002) analyzed the characteristics of the urban heat island of Shanghai using the 30-minute interval heat data from six automatic stations installed in the urban area of Shanghai during the period from December 1997 to March 1999. The results show that the occurrence frequency of the urban heat island in Shanghai is 87.8% and the monthly mean urban island intensity is greater than 0.8°C. The mean intensity is stronger at night and in autumn/winter than during the day and in summer. The position of the heat island core has a daily displacement. The core position will leave the city center whenever the weather is cloudless, calm, and has stable stratifica-

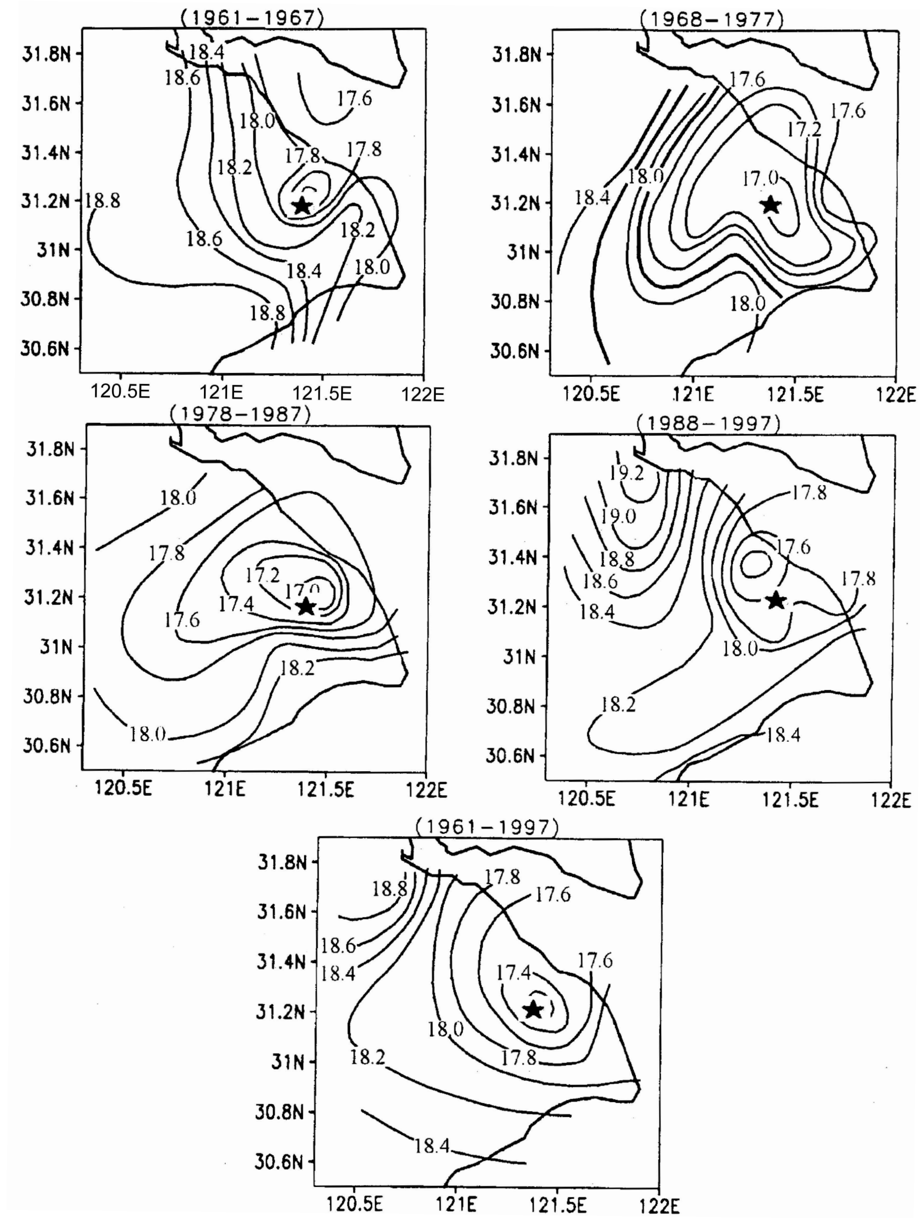

Fig. 2. Change in surface soil temperature (units: °C).

tion. Besides, many scholars have studied the circulation change caused by the urban heating using numerical models. So far, most of the analytic results have come from the few and short-range observations and their merits are a particularity, but the long-range characteristics of climate change and its mechanism need further study. In fact, there are enough stations in Shanghai City (including Longhua, Chongming, Baoshan, Jiading, Qingpu, Songjiang, Jinshan, Fengxian, Chuansha, Nanhui, and Minhang) and its adjacent area (Nantong, Changshu, Dongshan, Pinghu, and Jiaxing) which can provide enough long-range observation datasets to analyze the climate change of the heat island in detail. The monthly mean of ten elements of the 16 station mentioned above during 1961–1997 are collected, and the annual and seasonal linear trend of the elements and their possible mechanism are discussed in this paper. We propose some new facts and views about the linear trend of climate change and its possible mechanism based on the approval of conclusions reached by previous studies (Zhou, 1984, 1991; Zhou and Wu, 1987; Zhou and Shu, 1994). The results indicate that compared with the adjacent area, Shanghai City has the characteristics of a heat island of air temperature and maximum and minimum air temperature, a cold island of surface soil temperature,

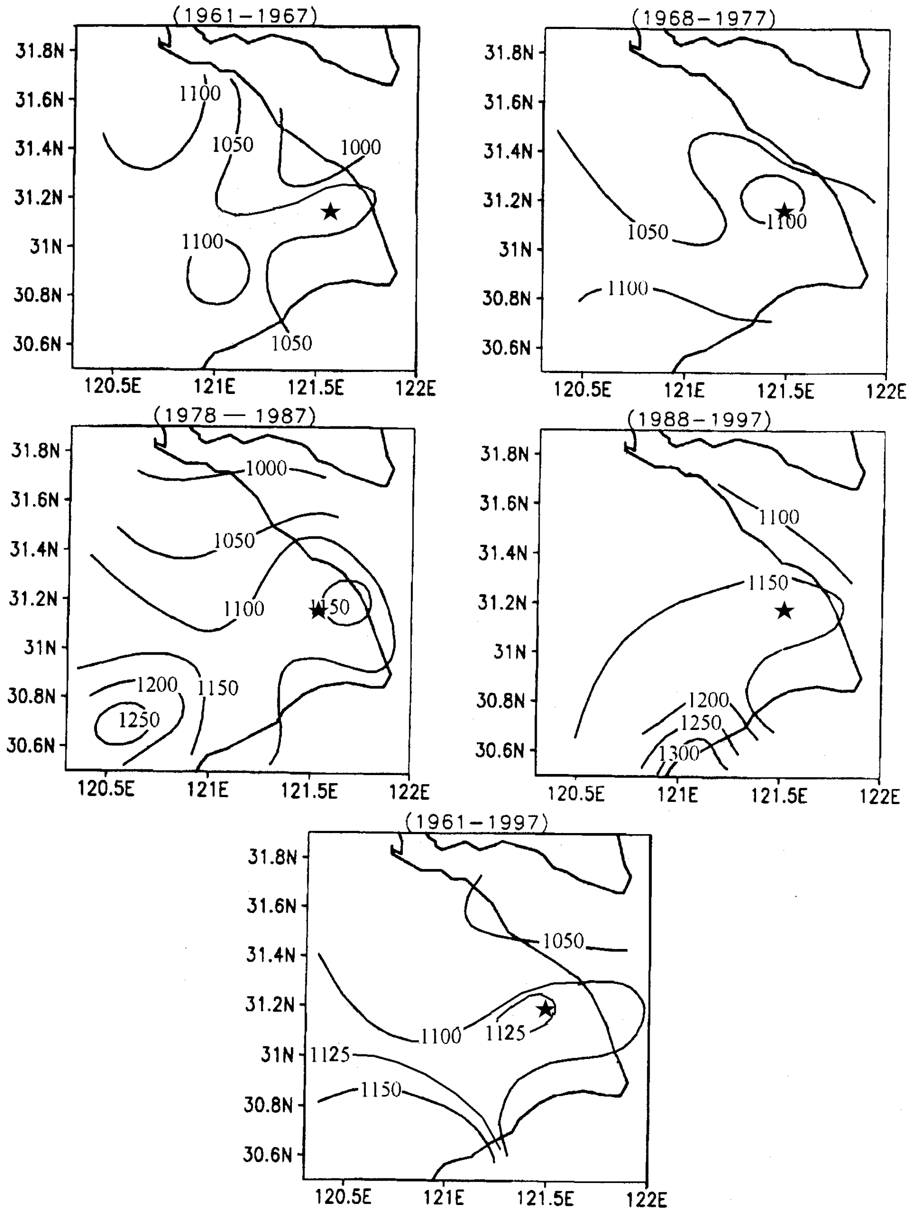

Fig. 3. Change in annual precipitation (units: mm yr^{-1}).

a rainy and cloudy island of precipitation and total cloud cover, a turbid island, and an island of poor visibility and sunshine duration. These effects grow as the economic development goes up. We suppose that the main mechanism of the enhancement of the heat island effect is the increase of energy consumption caused by economic development, and the cooling mechanism is the increase of turbidity.

2. Climate change of meteorological elements in the ground layer

The heat island effect is mainly revealed in the variation of the ground layer air temperature. Figures 1a–e show the distribution of annual air temperature in Shanghai and its adjacent areas for the periods of 1961–1967, 1968–1977, 1978–1987, 1988–1997, and 1961–1997, respectively. Figure 1f shows the distribution of stations used in this paper. Longhua station is located in the southwestern part of the urban district of Shanghai City and is selected to represent the urban station. The other stations shown in the figure are defined as suburban stations. It can be seen that the urban district of Shanghai (Longhua station) is an obvious warm center surrounded by a relative cold belt. Shanghai City can be treated as a big heat island in

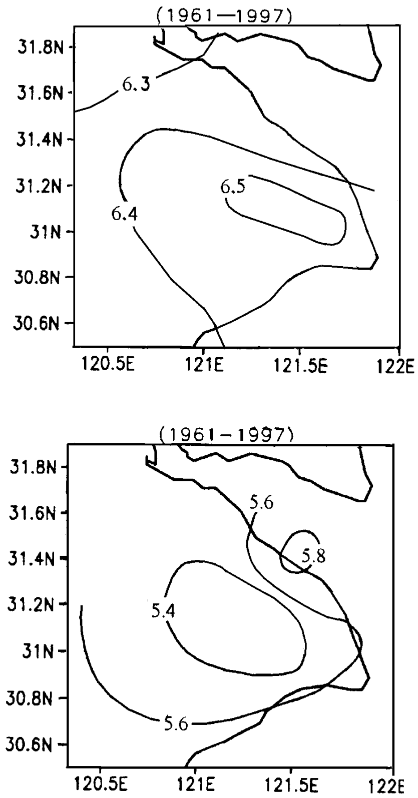

Fig. 4. Annual total cloud cover and sunshine duration (1961–1997), (a) total cloud (units: 1/10); (b) sunshine duration (units: h d^{-1}).

relation to its suburban areas, with a 0.6°C mean temperature difference between the warm center and cool belt (it may be 5°C in some instantaneous situations). For the different periods, the heat island effect is weak during 1968–1977, and afterwards increased rapidly during 1978–1987. The heat island effect is strongest during 1988–1997 with the difference in air temperature between the warm center and cool center exceeding 1°C. From the above discussion, we can conclude that Shanghai exhibits an obvious heat island effect and which gets weak after 1968 and strong after 1978. The intensity of the heat island may be associated with increasing energy consumption caused by economic development. The climate change characteristics of maximum and minimum air temperature are consistent with those of air temperature. The figures of these elements are not shown here due to the limitation of space.

It is worth noticing that the distribution of soil temperature is opposite to air temperature: surface soil temperature in the urban area is 1°C lower than that in the suburbs (Fig. 2a–e). It is obvious that the urban area of Shanghai is a soil cold island compared with the suburban stations. The intensity of the soil cold island has an obvious decadal variation. The cold center is located at the urban station during 1961–1987, and it moves northwestward from the urban center to Jiading station during 1988–1997. The value of the difference between the cool center and the suburbs is 1.2°C, 1.0°C, 1.0°C, and 1.3°C during four decadal periods, respectively. It can be concluded that the possible formation mechanism of the soil cold island may be associated with the decreasing of soil temperature which is caused by the strengthening of convection and precipitation.

The distribution of annual precipitation is shown in Fig. 3. For the climatic distribution during 1961–1997 (Fig. 3e), the precipitation decreased from the southern suburb to the northern suburb. There is a weak center located in the urban area. The rainy island has become stronger in recent decades. The precipitation difference between Longhua station and the northern suburb is 50 mm during 1968–1977, and it is more than 100 mm after the period of 1978–1987.

The climate distributions of total cloud and sunshine duration during 1961–1997 are shown in Figs. 4a–b. Figure 4b shows that there is a low center of sunshine duration located in the southwest urban district and adjacent suburbs (Longhua and Minhang stations). Minhang station is about 5 km southwest of Longhua. The climate distribution of total cloud (Fig. 4a) also shows a high center located in the urban area. The center of severe pollution is located in the urban area of Shanghai (Deng et al., 2002). This phenomenon is named the turbid island. In fact, there is also a low visibility center in the urban area (figure not shown).

The above results indicate that Shanghai City has the climatic characteristics of a heat island of air temperature and maximum and minimum air temperature, a cold island of surface soil temperature, a cloudy and rainy island, and a turbid island of visibility and aerosols. Besides these, a low center of sunshine duration is located at the southwest urban border and suburbs. These properties are enhanced with the development of the economy in Shanghai. In the last forty years, these characteristics are weak during 1968–1977 but become stronger after 1978.

Figure 5 shows the difference of annual air temperature between the stations of Longhua (urban center) and Songjiang (southern suburb), which is defined as the intensity index of the Shanghai heat island in Zhou et al. (1984), Zhou and Wu (1987), and Zhou (1991). It can be seen from the figure that the intensity index increased during the period before 1966, decreased during 1966–1978, and rapidly increased during the period after 1978. The intensity of the heat island increases with the economic development, which may be associated with increasing energy consumption. However, the enhancement of the heat island effect only affects the low layer atmosphere. The soil temperature cools caused by the increase of precipitation and

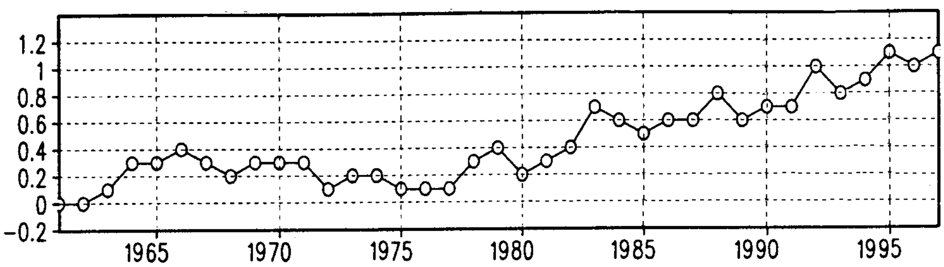

Fig. 5. Intensity index of the Shanghai heat island: the difference in annual air temperature between Longhua (urban) and Songjiang (suburban) (units: °C).

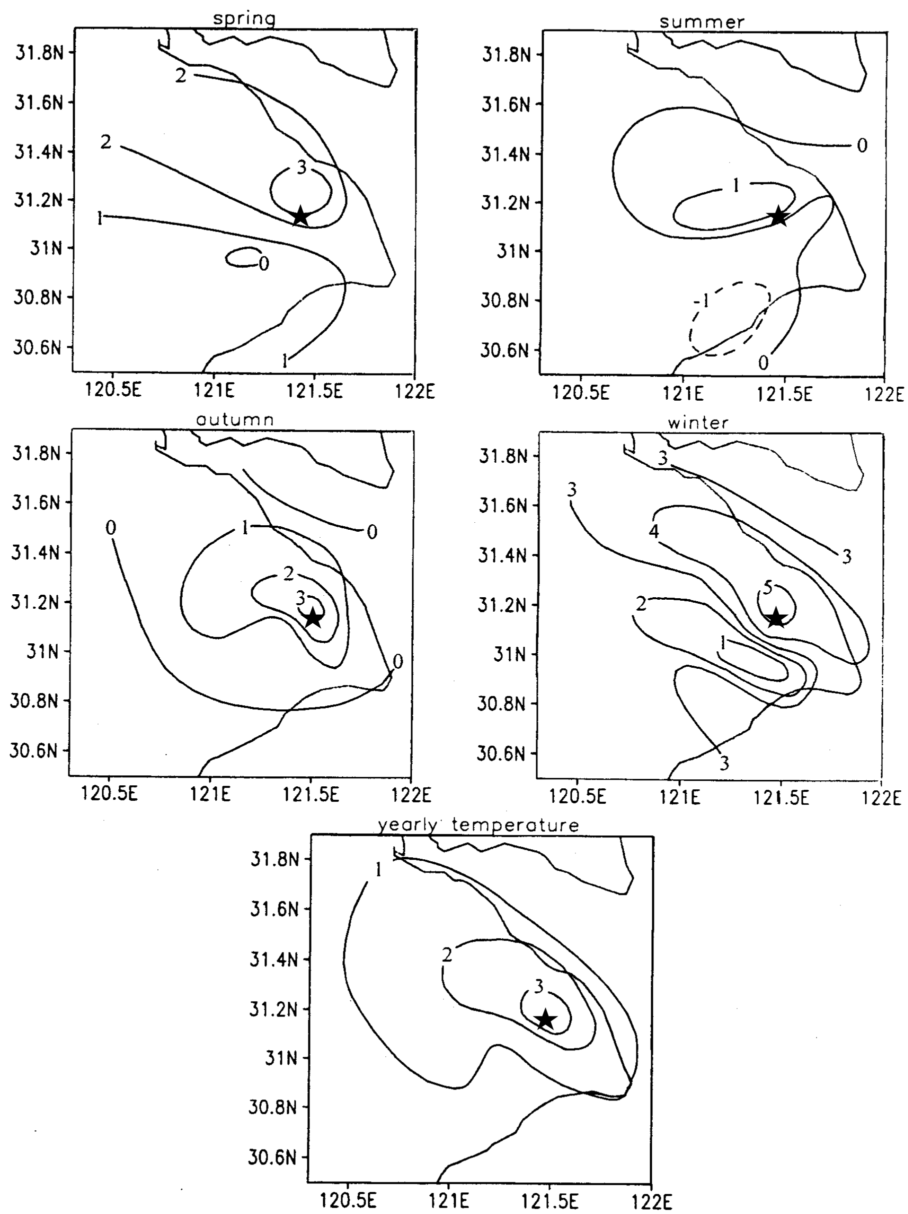

Fig. 6. Linear trend distribution of annual air temperature during 1961–1995 (units: $0.01°C\ yr^{-1}$).

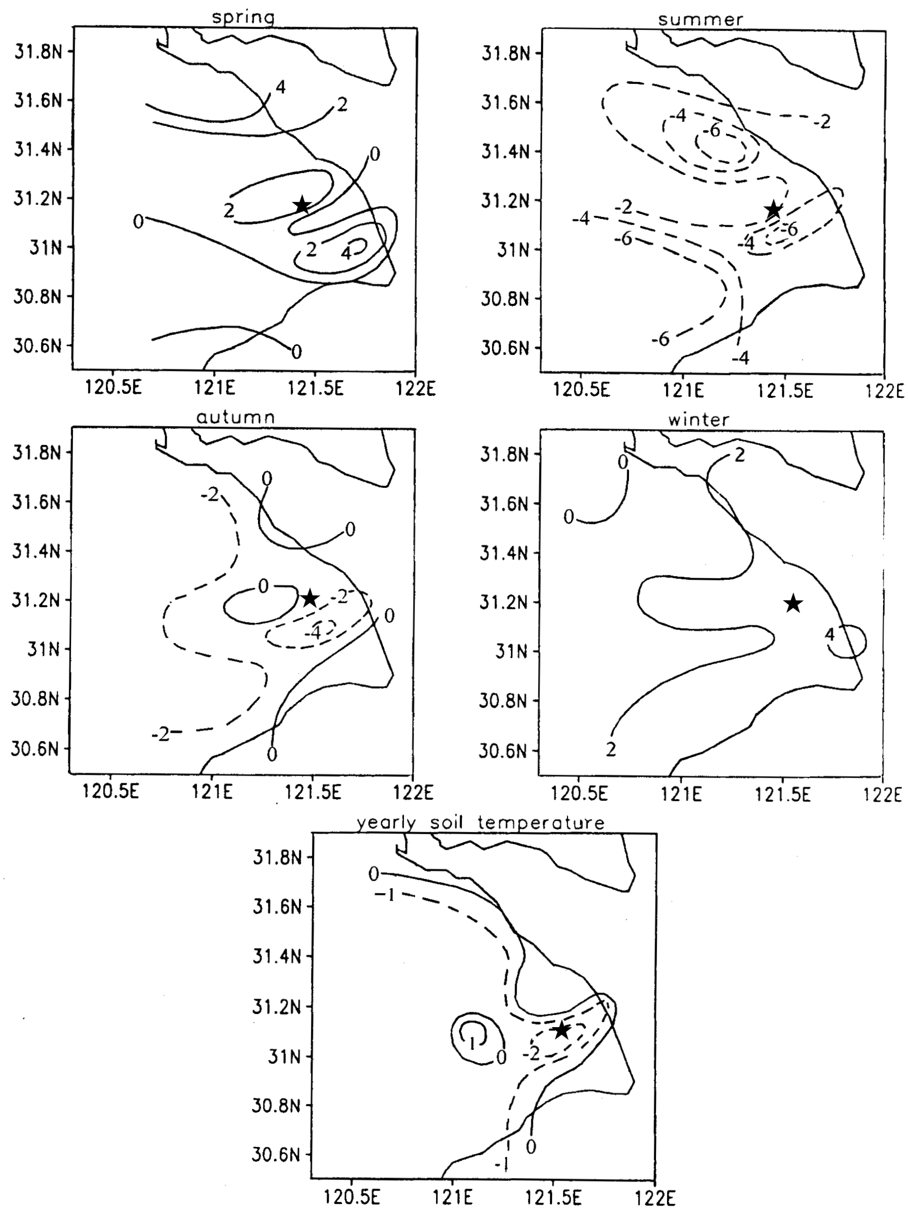

Fig. 7. Linear trend distribution of annual and seasonal soil temperature during 1961–1995 (units: 0.01°C yr^{-1}).

decrease of visibility and sunshine duration as the economy develops.

3. Linear trend of climate change in the Shanghai area

In order to analyze the climate change in the Shanghai area since 1961, the linear trends of annual and seasonal meteorological elements are calculated during 1961–1995; all trend values pass the 95% confidence level. It can be seen from the linear trend of annual and seasonal air temperature shown in Fig. 6 that the urban district is a positive center for annual and seasonal change; the positive value is largest in winter and smallest in summer. The linear trends of maximum and minimum air temperature are consistent with those of air temperature, but the maximum value of the minimum temperature trend is larger than that of the maximum temperature. For example, the center value of the annual trend of the former is 0.4°C $(10\,\mathrm{yr})^{-1}$ and that of the latter is 0.2°C $(10\,\mathrm{yr})^{-1}$. The seasonal change of the trend of maximum and minimum air temperature is also consistent with that of air temperature, being largest in winter and smallest

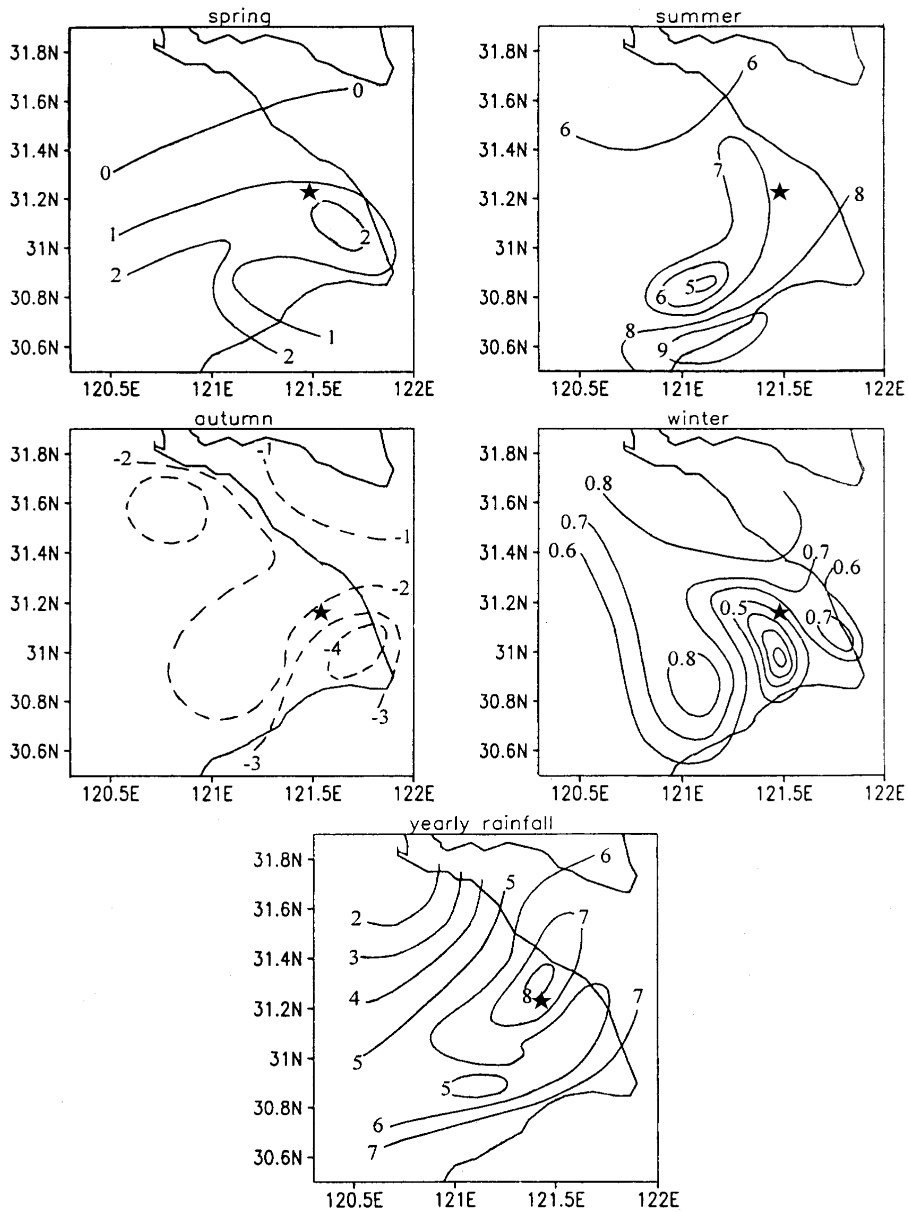

Fig. 8. Linear trend distribution of annual and seasonal precipitation during 1961–1995 (units: mm yr^{-1}).

in summer.

The linear trends of annual and seasonal surface soil temperature are shown in Fig. 7. For the values of annual trend, they are negative in the southern part of the urban area and for the southern suburban stations. However, they are positive for the Qingpu and Jiading stations (western and northern suburban stations). For the seasonal trends, the trend distributions are negative in summer and autumn, and positive in winter and spring. In other words, the cold island is getting stronger in the southern urban area of the city and the southern suburbs, but is getting weaker in the northern urban areas and western suburbs.

For the linear trend distribution of annual precipitation shown in Fig. 8, the positive trend covers the entire Shanghai City and has a positive center located in the urban district of Shanghai. It also has a low belt surrounding the suburbs. The precipitation trends of winter, spring, and summer are also positive, but it is feeble in winter. The trend of autumn precipitation is negative but it cannot compensate for the positive trend in summer, so the trend of annual precipitation is mainly attributed to that of summer.

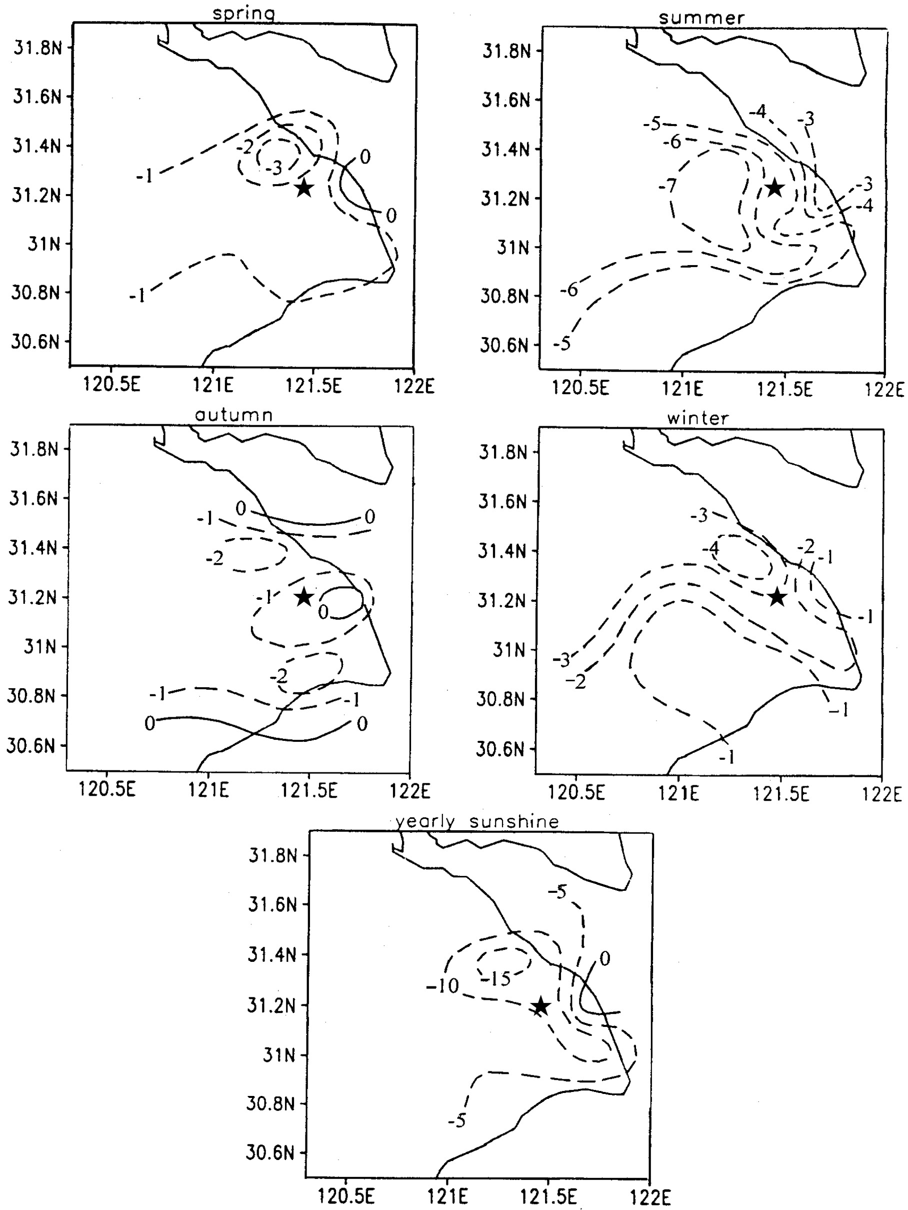

Fig. 9. Linear trend distribution of annual and seasonal sunshine duration during 1961–1995 (units: h yr^{-1}).

The linear trend distribution of sunshine duration is shown in Fig. 9. All the trends in the urban area and suburbs are negative with a center in the northern suburb. There is also a negative center located in the western suburb in summer, which is consistent with the increasing annual precipitation trend. The linear trend distributions of annual and seasonal visibility (figure omitted) are negative, which is in agreement with that of sunshine duration, but their centers are located in the urban area. These results imply that Shanghai is a turbid island, which is becoming stronger and stronger. The linear trend distribution of total cloud cover (figure omitted) also indicates that the urban area is an increasing center of cloud.

4. Possible mechanism for the heat island in Shanghai City

From the above discussions, Shanghai City has an obvious heat island effect of air temperature and maximum and minimum air temperature, a cold island of soil temperature, a weak rainy island of precipitation, and a turbid island of visibility and aerosols. Besides these, Shanghai City also has the characteristics of a cloudy island and sunshine duration island, but their centers are located in the southern part of the city district and suburbs. Based on the linear trends, it is shown that all the effects become enhanced during the period of 1961–1995 although the trend centers of several elements are not exactly located in the urban area. For the sunshine duration, the trend of the urban station (Longhua) is negative, but its trend center is located in a region about 5 km south of Longhua. Furthermore, the intensity of the heat island effect weakens and is enhanced with the economic development, slowly during 1968–1977 and quickly during 1988–1997.

Based on the above, we can conclude that the main factor causing the intensity of the heat island in Shanghai is associated with the increasing energy consumption due to economic development. It weakens (strengthens) as the economy develops slowly (quickly). The Environment Research Center of Peking University collected the energy consumption due to human activities in the Yangtze Delta and its adjacent area during 1995* and made a distribution map of annual heating intensity (W m^{-2}) for 1995. It shows that the heating intensity is 25 W m^{-2} in the urban area of Shanghai and 0.5 W m^{-2} in the suburbs. A numerical simulation was made by Chen (2002)** using a regional model forced by the heating of 1995. The result shows that the heating can cause more than 1°C warming in the urban area. On the other hand, the effect of the heat island will strengthen the convection and then increase the cloud cover and precipitation caused by the thermal difference. Besides the heating effect, the increase of aerosols caused by city development will strengthen the intensity of the turbid island, decrease the sunshine duration, and cause climatic cooling. Deng et al. (2002) analyzed the distribution of pollution aerosols in Shanghai by using satellite remote sensing data for 1987 and 1997. They showed that the distribution of pollution aerosols in Shanghai were enhanced and extended, and most of the urban district varied from light to serious pollution. The seriously polluted areas increased 51% from August 1987 to October 1997 (530 km^2 during 1987 to 801 km^2 during 1997), which is consistent with our conclusion.

The results by Deng R. R. et al. (2002) show that the aerosols can cause climate cooling in this area. The heat island in Shanghai is a result of a balance between the atmospheric heating and aerosol cooling. According to the results of our analysis, the heating caused by the increase of energy consumption is stronger than the cooling caused by the increase of pollution aerosols. Chen et al. (2002) studied the climate change in the Yangtze Delta and its adjacent area. The basic factors which caused the climate change are the same as those in Shanghai. The heating caused by the increase of energy consumption due to economic development is stronger than the cooling caused by the of increase pollution aerosols in the Yangtze Delta, but it is weaker than the aerosol effect in the adjacent area. It caused warming in the Yangtze Delta and cooling in the adjacent area, and then formed a regional heat island in the Yangtze Delta. The difference between the Shanghai and the Yangtze Delta heat islands is that the former in the urban area has combined effects which are stronger than that in the suburban area.

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REFERENCES

Chen Longxun, Li Weiliang, Zhu Wenqin, and Zhou Xiuji, 2000: Characteristics of environmental and climate change in Changjiang Delta and its possible mechanism. *Acta Meteor. Sinica*, **14**(1), 129–140.

Deng Ruru, Tian Guoliang, Wuang Xuemei, and Cheng Xaoxang, 2002: Quantitative remote sensing for synthetic aerosol and its application in Shanghai district. SPIE's Third International Asia-Pacific Environmental Remote Sensing Symposium, July 2002, Hangzhou, China, 125–129.

Ding Jincai, and Ye Qixin, 2002: The influence of the heat island effect on the forecasting and the diagnostic analysis of the high temperature in summer of Shanghai. *Developing Strategy of Atmospheric Sciences*, edited by China Meteorological Society, China Press, Beijing, 191–194. (in Chinese)

Ding Jingcai, Zhang Zhikai, Xi Hong, and Zhou Hongmei, 2002: A study of the high temperature distribution and the heat island effect in the mid-summer of the Shanghai area. *Chinese Journal of Atmospheric Sciences*, **26**(3), 412–420.

IPCC, 2001: *The Scientific Basis*. Contribution of Working Group *I* to the Third Assessment Report of IPCC, Cambridge University Press, 881pp.

Jones, P. D., P. Ya. Groisman, M. Coughlan, N. Plummer, W.-C. Wang, and T. R. Kar, 1990: Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, **347**(2), 169–172.

Karl, T. R., H. F. Diaz, and G. Kukla, 1988: Urbanization: Its detection and effect in the United States climate record. *Journal of Climate*, **11**(8), 1099–1123.

* Environmental Research Center of Peking University, 2002: Map of annual heating intensity due to the human activities in the area of Yangtze Delta during 1995.

** Li Weiliang and Zhu Wenqin et al., 2003: Seasonal climate characteristics of the regional heat island in Yangtze Delta and its formation mechanism. Accepted by "Meteorology and Atmospheric Physics".

Oke, T. R. (Ed.), 1984: Proceedings of the Technical Conference: Urban climatology and its applications with special regard to tropical areas WMO No. 652. W. M. O., Geneva.

Peterson, T. C., K. P. Gallo, J. Lawrimore, T. W. Owen, A. Huang, and D. A. McKittrick, 1999: Global rural temperature trend. *Geophysical Research Letters*, **26**(3), 329–332.

Yan Jiyuan, and Xu Jialiang, 1996: *Climate in Shanghai*, China Meteorological Press, Beijing, 249pp. (in Chinese)

Zhou S. -Z., 1991: Formation of fog and its characteristics in Shanghai. *Quart. J. Appl. Meteor.*, **2**(3), 256–263. (in Chinese)

Zhou S. -Z., and Wu L., 1987: Underlying surface temperature of Shanghai and urban heat island. *Acta Scientiae Circumstantiae*, **7**(3), 261–267. (in Chinese)

Zhou S. -Z., and coauthors, 1988: Turbid island effect of Shanghai City. *Scientia Geographica Sinica*, **8**(4), 305–312. (in Chinese)

Zhou Shuzhen, and Shu Tong, 1994: *Urban Climatology*. China Meteorological Press, Beijing, 618pp. (in Chinese)