SEASONAL AND ANNUAL TEMPERATURE VARIATIONS SINCE 1470 AD IN EAST CHINA

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ABSTRACT

The ten-year mean anomalies of seasonal and annual temperatures were reconstructed on the basis of historical documents of cold events such as severe snowing and freezing of lakes and rivers. The assorted events were calibrated with instrumental observations of temperature and transformed into ten-year mean anomalies. The reconstructed temperature series show predominance of cold climate in the first four hundred years of the period examined. The centenary seasonal temperature anomalies for the 16th to the 19th century vary between -0.1 and -0.7K. The coldest decades concentrated in the middle of 17th and 19th centuries. It provided the irrefutable evidence of the occurrence of the Little Ice Age in China. The minima of ten-year mean temperature anomalies ranged about -1.5 to 2.0K in spring and winter. Meanwhile, the variance of ten-year mean temperature was increased by more than 20% in comparison to the 20th century.

I. INTRODUCTION

The global averaged surface temperature has been increased by about 0.5K since 1850 AD (Wang, 1982). The 1980s becomes the warmest decade in the last 150 years or so (Jones, 1988). This warming was usually attributed to the increase of CO_2 in the atmosphere (Wigley, 1986). However, to estimate accurately the amplitude of the warming, knowledge of the temperature variations before 1850 is critical. It is true especially for the modern warming found in the 20th century that has followed a prolonged cold period from about 1550 to 1850, which is generally referred to as the Little Ice Age. Therefore, extending the temperature series to the period earlier than the instrumental time will contribute greatly not only to understanding the climatic change, but also to estimating the impact of greenhouse effect and predicting the trend in temperature variations.

Various proxy data such as tree ring series, ice cores and historical documents were used to reconstruct the paleotemperatures. The content analysis has been widely applied in China in examining temperature variations during historical time. Chu (1973) indicated that the fourth cold period in the last 5000 years occurred between the 15th and the 19th centuries with a temperature minimum of 1K or more lower than the modern observations. Zhang et al. (1976) found four severe cold phases in the last 500 years: 1470—1520, 1620—1720, 1840—1890 and after 1945. The minima of the temperature in the first three phases were about 1K lower than that at present. The aforementioned papers offered a basic understanding of climatic change in China, but some ambiguities still remained in the time scale and seasonality to be studied. Essentially those papers used only the evidence of winter severity to reconstruct the temperature series, and did not indicated whether the series was a ten-year mean or an annual one. Later, ten-year mean winter severity index series were obtained for each of eight regions over South China (Zhang and Zhu, 1981). Four cold phases were identified for the lower reaches of Changjiang River: before 1520—1540, 1610—1730, 1780—1900 and after 1950. The minima of ten-year mean anomalies were about -1.5K.

For avoiding the seasonal bias, the seasonal temperature series for summer were reconstructed independently (Wang Shaowu et al., 1989). Then, the assorted cold events were weighted with the instrumental observations of temperature (Wang Risheng et al., 1989). Recently, the technique of reconstruction was further improved. More information about the frost was joined into the analysis, It is especially important for getting a representative series in autumn and spring. In reconstruction of the winter series, not only the extremely cold, but also the extremely warm events were taken into consideration. In forming the summer temperature series more direct indications of cold climate were used instead of the indirect evidence such as flood or drought, though the summer temperatures usually correlate negatively with the precipitations. Finally, ten-year mean anomaly series of seasonal temperature were obtained for the period 1470 to 1988.

II. SOURCES AND PROCESSING OF DATA

For the scarcity of data characterizing the temperature anomalies, it is impossible to reconstruct the anomaly maps as it was done in studying the precipitation variations in historical time. Fortunately, the spatial scale of temperature anomaly is much greater than that of precipitation, so the region averaged temperature series instead of a single stational can be reconstructed.

Fig. 1 gives the correlation coefficients between the seasonal temperatures of Shanghai

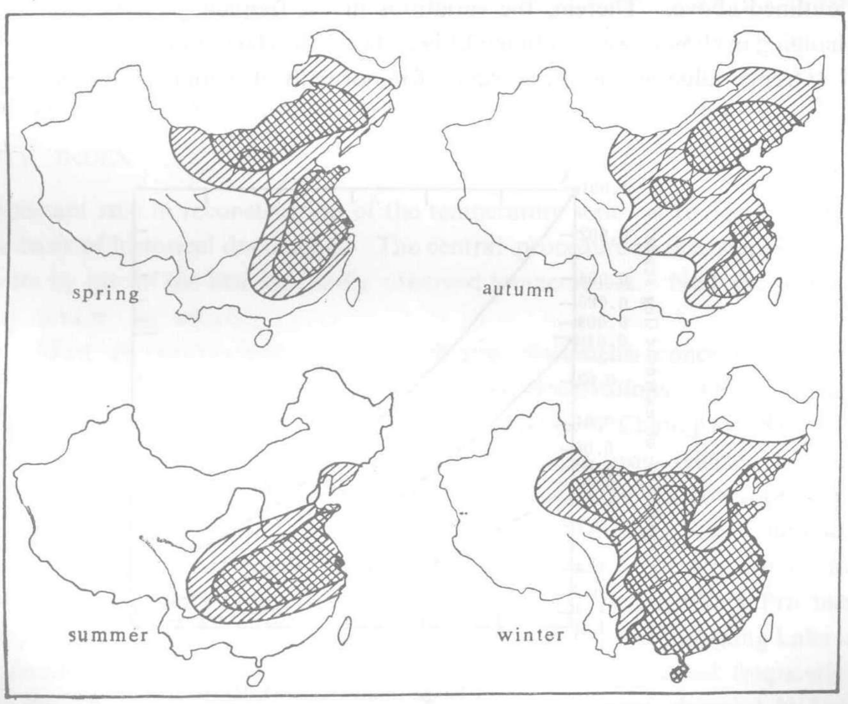

Fig. 1. Correlation coefficients between seasonal temperatures of Shanghai (dot) and elsewhere over China.

and elsewhere over China. The months used in making the seasonal mean are Dec. to Feb. (winter), Mar. to May (spring), June to Aug. (summer) and Sep. to Nov. (autumn). The shaded and cross-shaded areas are significant at 95.0% and 99.9% confidence level, respectively. Nearly the same result was obtained when other stations replaced Shanghai. Besides, EOF analysis also shows good accordance of seasonal temperatures over the lower reaches of Changjiang River. Therefore, it seems rational to reconstruct one temperature series for East China which covers mainly the lower reaches of Changjiang River, including Shanghai, Anhui, Jiangsu, Zhejiang and Jiangxi Provinces.

Another difficulty in content analysis of paleotemperatures was the bias of data towards the cold events. For example, the volume of processed historical data (Shanghai Meteor. Bureau et al., 1979) contains about twenty thousand items of the climatic calamities, but only one hundred among them concerned the warm episode. The years with unambiguous indications on the cold episode amounted to about 35% of the years examined, while the percentage decreased to 5% for the warm episode. Therefore, it is impossible to form a successive annual series of temperature as was done for the precipitation. However, it was found that the ten-year mean temperature anomalies closely correlate to the sum of the severity index in the decade (Wang Risheng et al., 1989). The severity index was taken as -0.5, -1.0 or -2.0 when the seasonal temperature anomaly was -0.5—-0.9K, -1.0—-1.9K or $\leqslant -2.0$K. Severity index of -1.0 coorresponds to ten-year mean temperature of -0.2K. Analysis shows validity of the correspondence for winter seasons is also found in spring, summer and autumn seasons. Consequently, the ten-year mean seasonal temperature anomaly series can be reconstructed when the severity index series were estimated from historical data sources.

A recently published paper of Wigley (1988) provided good arguments to support the approach outlined above. Therein, the variations in the frequency of the climatic extremes with the changing of climate were examined. Fig.2 shows the change in probability of exceeding a specified extreme value as the mean varies for normally distributed data. As an example,

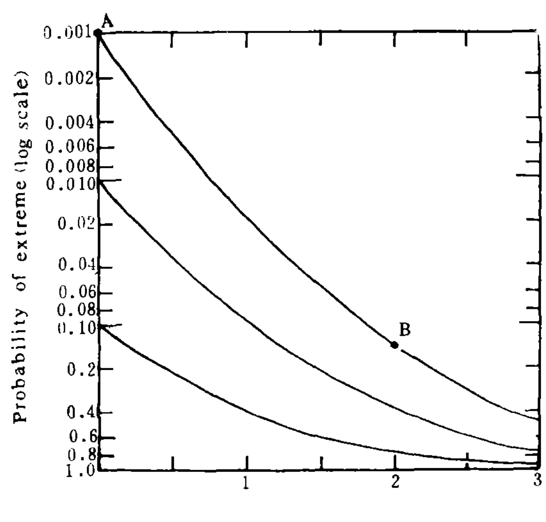

Fig. 2. Relationship between the changes of means and frequency of climatic extremes.

an event with an initial probability of $P=0.001$ (point A) becomes 140 times more likely ($P=0.14$, point B) if the mean is increased by two standard deviations.

One can use this diagram in a reverse way to find the change of mean value from the variation of frequency of cold events. Table 1 gives the frequency of cold events with different severity indices in seasons for Shanghai during 1873—1972.

Table 1. Frequency of Cold Events with Different Severity Indices during 1873—1972 in Shanghai

Seasons	Variance σ_T(K)	Severity index		
		−0.5	−1.0	−2.0
Spring	0.681	0.150(0.160)*	0.090(0.070)	0.000(0.002)
Summer	0.702	0.150(0.161)	0.100(0.075)	0.000(0.002)
Autumn	0.768	0.200(0.162)	0.080(0.091)	0.010(0.005)
Winter	0.970	0.130(0.152)	0.100(0.131)	0.040(0.020)

* Figures in the parentheses are the frequency calculated from normal distribution with the variance indicated.

The similarity of the figures observed and calculated manifests fine normality of seasonal temperature series of Shanghai. The cold events with severity indices of −0.5, −1.0 and −2.0 initially have the frequencies of 0.15, 0.13 and 0.02 respectively (see Table 1). Suppose the ten-year mean temperature was decreased by 0.5K, which corresponds to the winter variance of about 0.5, then the frequency would be increased to 0.30, 0.25 and 0.06 according to Fig. 2. Consequently, the sum of the severity index for that ten-year period would be increased (lowered in the negative value) as follows:
$[(0.30-0.15)\times(-0.5)+(0.25-0.13)\times(-1.0)+(0.06-0.02)\times(-2.0)]\times 10=-2.8.$
The severity index of −2.8 corresponds to the ten-year mean temperature of −0.56K. This is in good accordance with the proposed lowering of ten-year mean temperature. We may infer that the change of ten-year mean temperature can be estimated if the change of the frequency of cold events with different severity indices is identified correctly.

III. SEVERITY INDEX

The important step in reconstruction of the temperature series is to identify the severity index on the basis of historical documents. The central procedure in this step is to calibrate the cold events by use of the instrumentally observed temperatures. Now the procedure will be discussed season by season.

Winter: Most of the available data in historical documents concern the snowing or freezing of lakes and rivers. According to the recent observations (Feng et al., 1985), heavy snowing occurred along the lower and middle reaches of Changjiang River in winter of 1954—1955. In this winter the maximum of accumulated snow reached 1 m or more. Nearly all rivers but the Changjiang River were frozen with an ice cover of a few tenth to one meter thick. Another severe winter in the last a few decades was found in 1976—1977. At that time, the Bohai Sea was frozen with a deep ice. The sea water was frozen for more than five kilometers along the coast of Weihai port in Shandong Province. The maximum depth of the ice reached 0.6 m. Even the Taihu Lake and Dongting Lake in South China were frozen for a few days. Heavy snowing and glazing occurred frequently in this winter along the Changjiang River. Three snowing processes were observed in January of 1977 in Hangzhou, and the snow cover was kept for 24 days. In both 1954—1955

Table 2. Definition of Severity Index

Index	Spring	Summer	Autumn	Winter
-0.5	snowing, frost	prolonged rain, light snowing	prolonged rain, snowing, frost	heavy snowing glazing
-1.0	frost damage to grain, heavy snowing, glazing	frost, glazing, snowing, flood	frost damage to grain, heavy snowing, glazing	freezing on the ground, frozen well, frozen lake or river
-2.0	freezing on the ground, bitter cold, frozen lake or river	severe frost, bitter cold	frozen lake or river, bitter cold	bitter cold, frozen sea, frozen large lake or river

and 1976—1977 winters the seasonal temperature anomalies were about -2K over predominent territory of China. The winter of 1968—1969 was cold too, but with a little less severity, and the temperature anomaly was -1K or more in North China. The Bohai Sea and Huanghe River were frozen. The re-freezing of the Huanghe River in the late winter created serious ice-flood. The glazing was found over a extensive area of East China. Therefore, severity index for the winters with snowing only was defined as -0.5, and that with frozen lake or river as -1.0. Only in the winters with frozen large lake or the Changjiang River was the severity index given by -2.0 (see Table 2).

Summer: Seasonal temperature was closely correlated to the precipitation. For example, serious flood was observed along the Changjiang River in 1954, while the area with -1K or more temperature anomaly covered whole East China. In other summers with plantful precipitation the seasonal temperature anomalies varied between -0.3K and -0.5K, and the severity index was defined as -0.5 or -1.0. The summer frost means that the first frost may occur about two months earlier than the normal, then the seasonal temperature may be lowered by about 2K in comparison with the normal. Thus for the summers with frost the severity index was taken as -2.0.

Spring and autumn: It has been found that autumn temperature would decrease by 0.3K if the first frost occurs ten days early,and spring temperature would lower by 0.4K when the last frost appears ten days late. For example, the last frost was delayed in about ten days in 1957 and 1965. The spring temperature anomaly was about -0.5K. In 1970 and 1980 the last frost came about twenty days later than the normal, and temperature anomalies in both springs were -1.0K or more. The first frost was observed in ten to twenty days earlier than the normal in 1956 and 1976, while the autumn temperature anomaly was about -1K. Consequently, the autumns with earlier first frost or springs with later last frost twenty days or more than the normal, or the seasons with heavy frosting which seriously damaged the harvest were referred to as cold and denoted with severity index of -1.0 or -2.0.

There were some other descriptions on the cold events in the historical documents, such as wearing cotton jacket in summer, or passing of carriages over the frozen lake or river. In those seasons and in the seasons with severe frosting, snowing or freezing at least for two months the severity index was given as -3.0 . Four examples are given as follows:

Winter of 1670—1671. The Huaihe River was frozen for three months. Carriages passed through the river on the ice. Bitter cold. The wells and springs were frozen. Trees were withered. Snowing lasted for more than one month. Few passengers had been found on the way.

Autumn of 1493. Heavy snowing was prolonged from October through April of next year. More than one meter deep snow cover was accumulated. The visibility was significantly decreased. Rivers were frozen. No birds were found in the sky.

Summer of 1661. Snowing was observed in June. Frost was found in early June with bitter cold. Frost damaged the vegetables to death. Bitter cold occurred in early August, while snow and frost were observed.

Spring of 1628. Bitter cold with snowing appeared in March. Fish died in frozen river. Frost damaged the grain to death in April.

The extremely cold seasons with the severity index of -3.0 were identified. The chronicle of extremely cold seasons is given in Table 3. The winter of 1476 denotes that of 1476—1477.

Table 3. Chronicle of Extremely Cold Seasons

Spring	1519, 1588, 1595, 1621, 1628, 1721, 1743, 1746, 1786, 1801
Summer	1577, 1661, 1670, 1755, 1794, 1859
Autumn	1493, 1532, 1655, 1689, 1832, 1841, 1848
Winter	1476,1493,1501,1513,1596,1654,1655,1670,1683,1690,1795,1841,1845,1861,1877,1892

Moreover, to simulate closely the warm decades extremely warm events were identified in addition to the cold and extremely cold events. The severity index of an extremely warm season was given as $+1.5$. However, only the descriptions which really indicate an extremely higher temperatre than the normal were considered in identifying the extremely warm events. The events such as droughts or re-flowering of fruit trees were omitted, for they link in general with a warmer season, but not must be an extremely warm one. Four examples are outlined in the following.

Winter of 1522—1523. Warm as in spring.

Autumn of 1759. Extremely warm in September. The roots of grain were eaten by the insects.

Summer of 1671. Extremely hot. No rain from June through August. Grass and trees were withered.

Spring of 1872. Hot in April as in summer.

The extremely warm seasons are listed in Table 4. Altogether 32 extremely warm seasons were identified, which was a little less than the total number of extremely cold seasons (39). But 11 of 32 extremely warm seasons occurred in the 20th century. Meanwhile, no one extremely cold season was found in this period. It manifested well the warming of the climate in China at present time.

As a result, the cold and extremely cold events and extremely warm events were identified from 1380 through 1988. The next step is to transform severity index into the ten-year mean temperature anomalies.

Table 4. Chronicle of Extremely Warm Seasons

Spring	1474, 1618, 1639, 1872, 1919, 1928, 1941
Summer	1526, 1592, 1671, 1692, 1714, 1738, 1934, 1953
Autumn	1732, 1759, 1768, 1855, 1925, 1945, 1946
Winter	1497, 1522, 1544, 1612, 1695, 1703, 1786, 1940, 1945, 1978

IV. TEMPERATURE SERIES OF 1880—1979

The important step in transforming the severity index into the temperature anomaly is to find a temperature series, which is long enough and representative for the studied region. The temperature grade data set provided the only one homogeneous temperature series in China, then it was used in calibration (Beijing Meteorological Center, 1982). The temperature grades are expressed by the figures of 1 to 5, which represent much warm, warm, normal, cold and much cold, respectively. The grades are defined by the frequency, so the frequency of grades 1 and 5 was 12.5%, and that for the other grades was 25%. First, the grades were found for each station and for each month. Then, three month averages were taken to form a seasonal mean. Finally, regional mean was obtained by averaging the seven stations, Shanghai, Nanjing, Hankou, Yichang, Changsha, Zhijiang and Wenzhou. The coverage of these stations is nearly the same as in examining the historical documents, so it was used as a representative data set.

Multiplying the averaged grades by ΔT, one can get the seasonal temperature anomaly, here ΔT was 1.0K, 0.8K, 0.9K and 1.2K for spring, summer, autumn and winter, respectively. ΔT is the average difference between the temperatures for each two successive grades, 1 and 2, 2 and 3, and so on. The grade series began at 1910 , so the anomalies for decades, 1910s, 1920s,..., 1980s were calculated by averaging the ten seasonal anomalies. They were given in Fig. 3 by dotted line. In comparison with them the ten-year mean temperature anomalies were also calculated based on severity index data set, and drawn in the same diagram by solid line.

Fig. 3 shows good parallelism between two series. It indicates that the ratio of severity indices, -2.0 to -1.0, which were found in previous paper(Wang Risheng et al., 1989), is also acceptable for the other seasons besides winter.

In addition, for getting a rational anomaly the usage of an apposite normal is very important. A period of seventy years (1910—1979) was a little shorter, and covered mainly the warming in the 20th century. Therefore, the 100 year period from 1880 to 1979 was taken to form a normal. It consists of not only the warming phase, but also the ending part of the last cold phase, Little Ice Age. Therefore , the temperature anomalies calculated from the grades since 1910 were also reduced to the anomalies which referred to the 100 year normal.

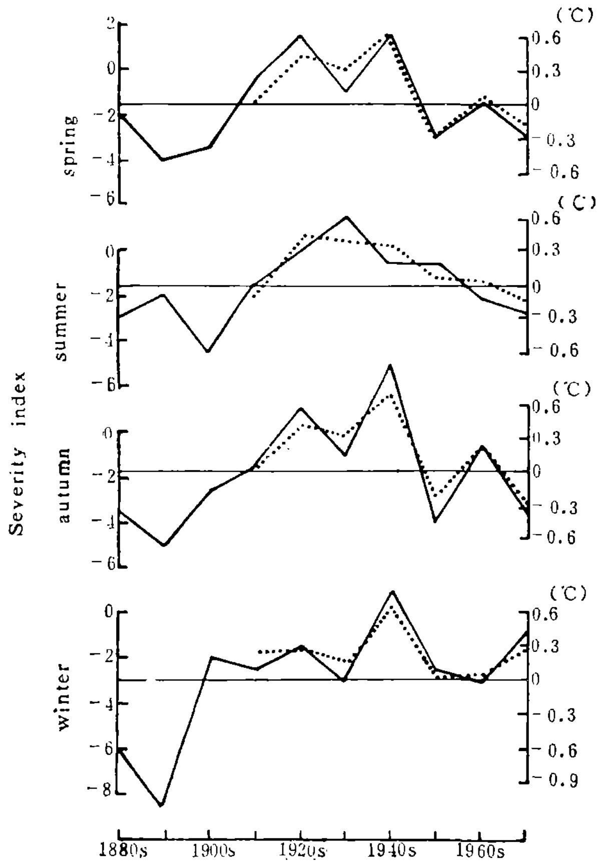

Fig. 3. Ten-year mean seasonal temperature anomalies based on temperature grades (dotted line) and severity index (solid line).

V. TEN-YEAR MEAN TEMPERATURE ANOMALIES SINCE 1470

Once the severity index is found for each season and decade, it is easy to reconstruct the ten-year mean temperature anomalies by multiplying 0.2 and subtracting the normal. Fig. 4 shows the temperature anomaly series for the seasons of spring, summer, autumn and winter. The ordinate on the left indicates the severity index, and that on the right denotes the temperature anomaly.

This section will concentrate on discussion of the general characteristics in change of ten-year mean temperature anomalies. The results are as follows:

(1) The number of decades with the temperature anomalies lower than the average for the period before 1880 (shaded areas in Fig. 4), varies from 10 in autumn to 15 in winter.

(2) The minimum of temperature anomalies reached -1.5K in autumns of the 1530s and the 1650s, and in winters of the 1650s and the 1840s. The ten-year mean temperature anomaly in winter of the 1840s even reduced to about -2K. But in summer temperature anomalies were rarely below -1K.

(3) None of decades was found with temperature anomaly below -1K in the present century. Only summer temperature anomaly in the first decade of the 20th century was

lower than that averaged for the period before 1880.

(4) The maximum of ten-year mean temperature anomalies was found in the 1940s in all the seasons but summer, the maximum anomaly of which occurred in the 1930s. The maximum of positive anomaly was approximately 1 K in the autumn of the 1940s. The maxima for other seasons vary between 0.6 and 0.8 K.

(5) Fig. 5 shows the ten-year mean annual temperature anomalies. Temperature anomalies$\leqslant -0.5$ K were found in the early 16th century, middle 17th century and middle 19th century. These are the three cold periods in East China during the Little Ice Age.

(6) The centenary annual temperature anomalies for the 16th, 17th, 18th and 19th century were -0.53 K, -0.63 K, -0.42 K and -0.63 K respectively. We may infer that the temperature in the Little Ice Age as a whole was about 0.5K lower than that in the last 100 year period.

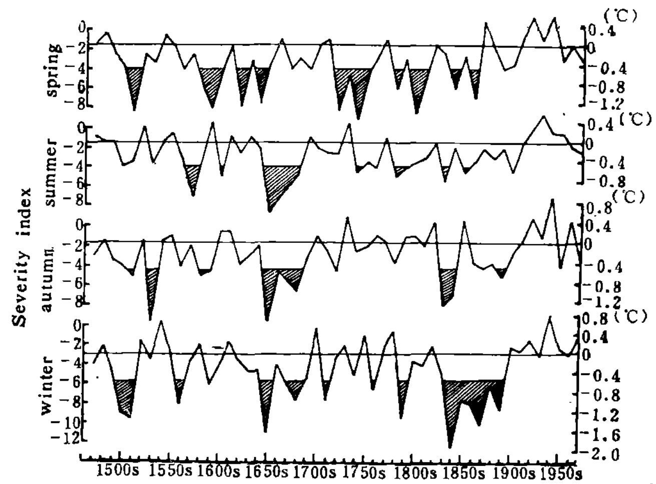

Fig. 4. Ten-year mean seasonal temperature anomalies (negative anomalies lower than the average for the period before 1880 are shaded).

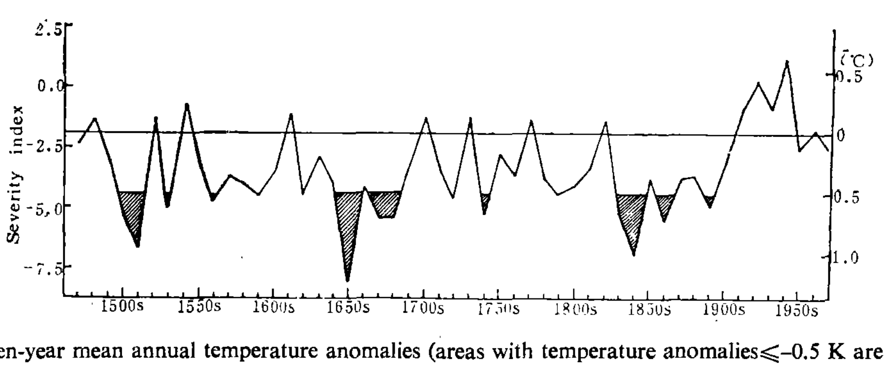

Fig. 5. Ten-year mean annual temperature anomalies (areas with temperature anomalies$\leqslant$-0.5 K are shaded).

One can conclude that the reconstruction of paleotemperature in East China approved of the occurrence of the Little Ice Age, in which three cold periods were identified. The warming found in the 20th century was developed on the background of the last cold period of the Little Ice Age. Therefore, the warming trend observed during 1850s—1980s may be overestimated in the sense of greenhouse effect.

VI. THE CHARACTERISTICS OF LITTLE ICE AGE

Studies on the climatic change have been focused on the change of the mean temperature. However, the variance seems to change with time also. The evidence was the greater increase of the frequency of extremely cold events than the cold events with less severity index. Meanwhile, if the variance increased without lowering the mean temperature, then the frequency of extremely warm events should be increased also. But it was not the case. Therefore both the means and the variances, might change during the Little Ice Age.

To illustrate this idea in detail, Fig. 6 gives six scenarios, which are chosen to simulate the change in frequency distribution of the temperature population in response to the change in the means and variances. In all the six panels the full curve gives the initial normal distribution with the mean temperature $\overline{T}=0$, and the variance $\sigma_T=1.0$ K. The shaded areas in Fig. 6 show the change in frequency distribution when the mean or variance, or both are changed. The ideal change in the frequency of the cold events with different severity indices is given in Table 5. The data sources of Table 5 and Fig. 6 are the same

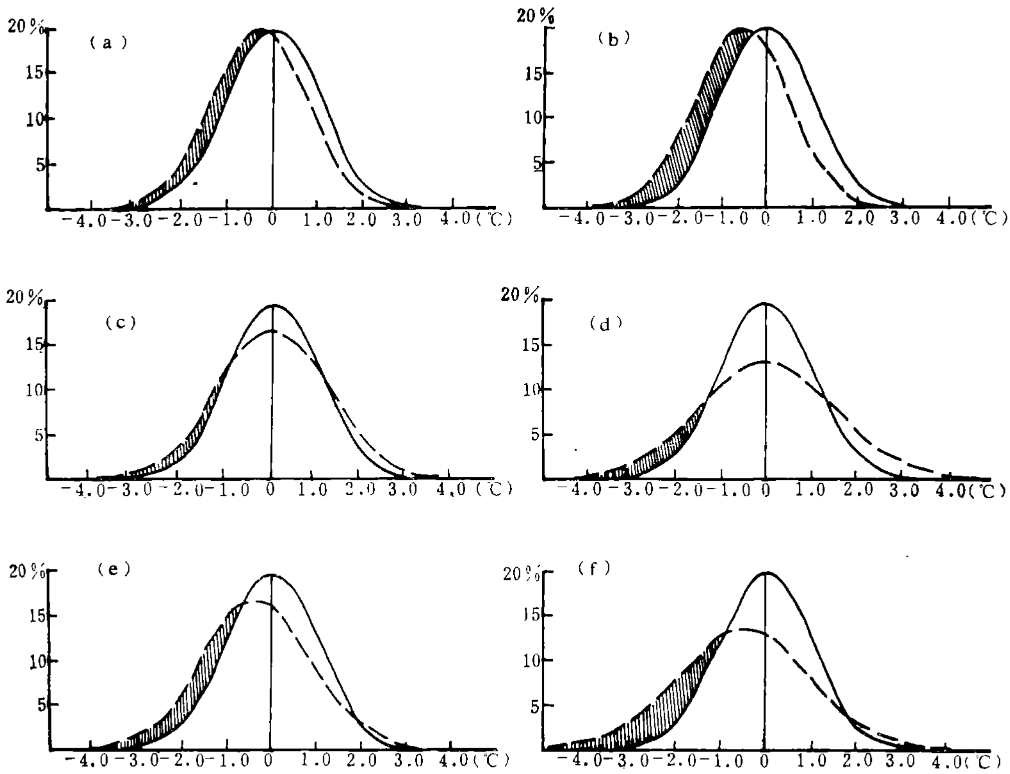

Fig. 6. Six scenarios with different means and variances. (Full line: $\overline{T}=0$, $\sigma_T=1.0$K, broken line: (a) $\overline{T}=-0.3$K, $\sigma_T=1.0$K; (b) $\overline{T}=-0.5$K, $\sigma_T=1.0$K; (c) $\overline{T}=0.0$K, $\sigma_T=1.2$K; (d) $\overline{T}=0.0$K, $\sigma_T=1.5$K; (e) $\overline{T}=-0.3$K, $\sigma_T=1.2$K; (f) $\overline{T}=-0.5$K, $\sigma_T=1.5$K).

(Yao, 1963). The change in frequency of the cold events in the first four centuries was outlined in Table 6 for comparison with the ideal one in Table 5. In summers and winters during the Little Ice Age the decrease of the mean temperature seemed to occur without any change of the variances (scenarios a and b). But the variances likely changed in springs and autumns (scenarios e and f).

Table 5. Differences in Frequency of Cold Events in Six Scenarios

Scenarios	$\bar{T}$	σ_T	Severity Index			
			−3.0	−2.0	−1.0	−0.5
a	−0.3	1.0	0.3	1.9	6.1	2.9
b	−0.5	1.0	0.5	3.9	10.6	4.1
c	0.0	1.2	0.5	2.0	1.8	−1.3
d	0.0	1.5	2.2	4.6	2.7	−3.4
e	−0.3	1.2	1.1	4.3	6.7	0.2
f	−0.5	1.5	4.7	8.9	7.5	−2.0

Table 6. Differences in Frequency of Cold Events in the Period before 1880

Season	Severity Index				Similar Scenarios
	−3.0	−2.0	−1.0	−0.5	
Spring	2.5	6.3	0.5	−0.5	f
Summer	1.8	3.0	3.3	1.8	a
Autumn	1.8	2.8	0.8	−0.5	e
Winter	2.3	2.0	2.8	7.0	b

In the end, it is worth noting that reconstructed series is extended only to 1470 in the present paper, but it does not mean the Little Ice Age started exactly in 1470. The efforts are being made to extend the series backward to the early time and to reconstruct the paleotemperature series for the other regions in China.

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