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AN APPROACH TO RECONSTRUCTION OF TEMPERATURE ON A SEASONAL BASIS USING HISTORICAL DOCUMENTS FROM CHINA

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ABSTRACT

A methodology is presented for reconstructing past climates on a seasonal basis using historical data from chronicles and documents in China. This procedure consists of three steps: first, individual climate indicators are identified and scaled by ordinal numbers (or grades) based on their individual statistics; secondly, the cold (warm) climate index is defined as a function of the scaled indicators. Finally, the climate index is calibrated in terms of temperatures by regression with recent observations. This methodology is applied to constructing the temperature series of the last 500 years in China, based on which climate variations are studied. Spectrum analysis shows variability in about 200, 80, 30, and 22-year cycles.

KEY WORDS Historical data Climate indicators Variables of reconstruction Cold (warm) index Calibration

1. INTRODUCTION

To understand climate changes it is necessary to develop our knowledge about the history of climate. As continuous climate series of instrumental measurements are usually short, for most areas of the world no longer than a few decades, which is inadequate for the purpose of studying climate variations, various kind of proxy data collected from different sources, such as lake and sea sediments, tree rings, and ice cores, which are referred to as environmental data, have commonly been used to alleviate this problem. Additionally, very valuable information about local weather and climate is included in historical documents and writings in many parts of the world, and this is generally referred to as historical data. Since the historical data can be associated conveniently with specific climate parameters, and are reliable, easily interpreted, and accurately dated, they are also widely used in climate reconstructions (Lamb, 1977; Ingram *et al.*, 1981a, b). In China, fragmentary instrumental observations of temperature were made as early as AD 1741, with unbroken series back to 1871 (Chu, 1936, 1973). Owing to its long and continuous history, China possesses a huge wealth of historical documents and written material, many of which contain information about weather and climatic conditions at that time. The earliest written records about weather and the related phenomena can be dated back to circa eighteenth to twelfth century BC, which were engraved on the so-called 'oracle bones'. More detailed information was recorded after the invention of paper. In his classical paper of 1973, now the most quoted one so far as climate changes in China are concerned, Chu divided the past 5000 years into four periods according to the features and sources of the historical materials, i.e. the archaeological period (3000 BC–1100 BC), the phenomological period (1100 BC–1400 AD), the local chronicle period (AD 1400–1900) and the instrumental period (from AD 1900 to present). A good summary about these data can be found also in the book by Domrös and Peng (1988) and in the recent paper by Wang and Zhang (1988).

The earliest study of climate changes in China based on historical materials began in the 1940s (Hu, 1944). The work by Chu (1973), which provides a landmark in the development of our knowledge of the past climate in China, inspired scientists in China to collect and compile relevant historical data from various sources.

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Recent publications of written records about natural calamities and unusual weather and climate phenomena on a local and chronicle basis, should be mentioned: *The Historical Materials about Natural Calamities in Haihe River Basin* compiled by staff members of the Drought and Flood Research Group of Hebei Province (1985), the *Historical Materials about Hydro-climate in Henan Province* by the members of the General Hydrometric Station of Henan Province (1982), *Data of the Historical Climate over East China During the Recent 500 Years* by collaboration of the joint staff members from seven research units (Meteorological Bureaux of Shanghai, Jiangsu and others, 1978). Studies on climate reconstruction based on these data sources carried out in recent years (e.g. Zhang, 1980; Wang and Zhao, 1981; Wang and Wang, 1988, 1989) indicate great potential for the extraction of information about past climate from the historical materials kept in China. Encouraged by the work of Pfister (1981), we tried to develop a procedure of data management suitable for computer handling and a method of climate reconstruction based on quantification of written records into variables equivalent to climate parameters and their related calibration. It was aimed at making further use of the information that can be extracted from historical data for climate reconstruction, in terms of accuracy and resolution in time. In this paper, we first describe the methodology of this approach and then apply the method of reconstruction and the related calibration to reconstruct a temperature time series of the last 500 years based on the historical data for eastern China.

The basic idea of using historical data to reconstruct a climate series is the derivation of climatic parameters, for example temperature, from the natural phenomena, happenings or facts—called climate indicators (or indicators of climate anomalies); these are, the arrival of migratory birds, blossoming dates, first and latest frosts, freezing of rivers, lakes and sea, duration of overcast skies and rain, recorded descriptions of warmth and coldness, price of rice, quality of harvests, and many other phenomena that are governed by or related to meteorological factors. Knowledge of the relationship between these indicators and a climate parameter, which is usually established on the basis of instrumental observations, serves as a criterion for calibration, i.e. the transformation of the reconstructed indicator series into a series of the relevant climatic parameter. Through his perseverance on a huge amount of historical materials, Chu (1973) carried out a reconstruction of temperature series, and convincingly showed the long-term climate changes in China during the last 5000 years. Such an achievement is largely the result of his ingenuity in moulding different aspects of the indicators into a synthetic yet coherent and consistent series of temperature, which is not possible without a profound and wide knowledge about history and natural sciences. Nevertheless, his method can hardly be programmed into a systematic procedure available for computer manipulations, and thus there are still possible improvements to be made by making intensive use of the available historical data through computer based processing. Moreover, it is desirable to reconstruct the climate series on a quantitative basis and with a better resolution of time-scale. Zhang (1980) carried out a reconstruction of winter temperature for the last 500 years in China using historical data on a quantitative basis. By defining the cold and warm winters according to the relevant indicators mentioned above, he was able to transform the written records into a climatic parameter (temperature) through a calibration of regressions between the frequencies of cold and warm winters and the corresponding 10-year mean winter temperatures. This is also the basic idea of the approach presented here, in which we particularly consider the following two aspects that are not covered by Zhang's method: first, the indicator for a specific climatic parameter, say temperature, depends on its statistical or physical relationship to the parameter—a winter with heavy snow may reflect a different degree of coldness from one indicated by freezing of rivers or lakes. Secondly, the degree of climate anomaly indicated by an indicator in a given place usually changes according to the time and duration of the recorded events as well as its intensity. For example, the freeze-up of a lake for over a month indicates a colder winter than one indicated by a freeze-up of lake for a few days (Wang and Wang, 1989). Based on this consideration we developed our procedure for climate reconstruction using historical data, which can be conveniently programmed into a computer if the data are processed in the way suggested in the following section.

2. METHODOLOGY

One typical feature of historical data is that, owing to the lack of systematic observations for special purposes, there are no prescriptions for the items and their formats. The records cover a wide spectrum of phenomena and events related to extremely cold or warm conditions, which are usually associated with agricultural damage or disasters, and these can serve as indicators of climate anomalies. As the requirement of climatic state for the occurrence of each individual indicator varies, some indicators appear in the record more often than others. Each has its own characteristic domain of temperature anomaly, but none of them are continuous in time or space. Because of this fragmentary picture, it is necessary to consider as many indicators as possible in order to produce a relatively consecutive and coherent series representing the climatic variation of a certain region. For this purpose the following procedures are established, which consist of three steps: first, the individual indicators are identified as variables of reconstruction (VR) and scaled by ordinal numbers; secondly, cold (warm) climate index series are constructed as a function of these variables; finally, the temperature series is reconstructed by calibrating the climate index through regression with recent observations.

2.1. Identification of climate indicators

A set of L climate indicators is identified by L variables of reconstruction, VR(k), with $k=1, 2, \ldots, L$, which is scaled by ordinal numbers from 0 to 3 in accordance with the intensity of the relevant events:

$$\begin{aligned} \mathrm{VR}(k) &= 0,\ 1,\ 2,\ \text{or}\ 3 \\ &= \text{no record, existing, severe, or extremely severe} \end{aligned} \tag{1}$$

Each individual VR(k) of a particular season and location in a certain year is evaluated by its overall frequency distribution such that the occurrences of the indicator with VR(k)=0, 1, 2, and 3 roughly follow a Gaussian distribution. In practice: VR(k)=1, when recorded events about the indicator are comparable to the extreme cases observed in recent decades; VR(k)=3, when the events are regarded as 'extreme' even for the whole historical period under consideration; VR(k)=2, when the intensity is between the two (An example is given in Table II). In this way, a consistent seasonal series of VR(k) at a given place can be obtained. Here it should be noted that the values of VR(k) are naturally related to the intensity of the climatic anomaly in terms of the temperature grades defined in *Data of Temperature Grades in China: 1911–1980* (Meteorological Centre of Beijing, 1982) or in terms of a warm or cold temperature anomaly (TA) defined on an ordinal scale:

$$\begin{aligned} \mathrm{TA}_+ &= 0,\ 1,\ 2,\ \text{or}\ 3 \\ &= T<\sigma,\ 2\sigma>T>\sigma,\ 3\sigma>T>2\sigma,\ \text{or}\ T>3\sigma \end{aligned} \tag{2a}$$

$$\begin{aligned} \mathrm{TA}_- &= 0,\ 1,\ 2,\ \text{or}\ 3 \\ &= T>-\sigma,\ -2\sigma<T<-\sigma,\ -3\sigma<T<-2\sigma,\ \text{or}\ T<-3\sigma \end{aligned} \tag{2b}$$

where T is seasonal temperature and σ is a constant positive number. The VR(k) and TA values are not necessarily identical, as the values of VR(k) depend solely on the individual statistics of the indicator.

For computer manipulations, the information about an individual indicator of a climate anomaly is conveniently identified in the form of $I=\{$YEAR, SEASON, LOCATION, k, VR(k), description$\}$, where 'description' is the statement, based on which the value of VR(k) is given. Here the year, season, and location (longitude and latitude, and if necessary, altitude) are also treated as parameters, so that the input of data does not necessarily follow a special order of time or location. The advantage of this arrangement of historical data lies in its flexibility, with which one can produce records of a given year, a given season or a given region for a special purpose, or combine them.

2.2. Definition of a warm and cold climate index

Next, the climate indicators are categorized according to their relation to cold and warm climates:

$$\{\mathrm{VR}(k),\ k=1,\ 2, \ldots, L\} = \{\mathrm{VC}(i),\ i=1, \ldots, L1;\quad \mathrm{VW}(j),\ j=1, \ldots, L2;\quad L1+L2=L\} \tag{3}$$

As these indicators are related to temperature anomalies of different intensity, a suitable combination leads to a relatively continuous and coherent series, the distribution of which is comparable to that of the ordinal scale temperature anomaly (TA) defined by equation (2). Furthermore, as each indicator is evaluated according to its own statistics, one indicator occurring more often than the other means that the latter indicates a colder (or warmer) condition than the former at the same values of the corresponding variable of reconstruction VC (or VW). To avoid this discrepancy, different weights have to be introduced when combining them. Instead of linear combination we use the maximum function (max) to prevent exaggerations if more than one indicator appears in the records of the same year. This leads to the categorized warm and cold climate indicators

$$\mathrm{W} = \max\,(a(i) \times \mathrm{VW}\,(i),\quad i = 1, 2, \ldots, L1) \tag{4a}$$

$$\mathrm{C} = \max\,(b(j) \times \mathrm{VC}\,(j),\quad j = 1, 2, \ldots, L2) \tag{4b}$$

where $L1 + L2 = L$; $a(i)$ and $b(j)$ are coefficients (relative weights) of VW(i) and VC(j), which are determined by examination of recent observations and by comparing the frequency of their occurrence with respect to the other VWs and VCs.

The historical data emphasize extreme anomalies of weather or climate. Therefore, the reconstructed climate indicator (C or W) series basically provide lists of cold or warm extremes of different strength. They can be related directly (section 2.3) to an observed reference time series of temperature (T) after transformation into the ordinal scale temperature anomaly (TA) as described in equation (2). In this sense, the C (or W) series and the TA_- (or TA_+) series are equivalent.

To obtain a continuous time series of a certain resolution, M, the cold (warm) climate index, IC (IW), is introduced as the sum of the ordinal scale temperatures, TA_- or TA_+, and related to the cold (warm) climate indicator, C (W):

$$\mathrm{IW} = [\mathrm{TA}_+] = [\mathrm{W} \times p(\mathrm{W})] \tag{5a}$$

$$\mathrm{IC} = [\mathrm{TA}_-] = [\mathrm{C} \times p(\mathrm{C})] \tag{5b}$$

where [ ] denotes the sum of M consecutive years, and the related average is denoted by over-bar and equal to [ ]/M; M is the resolution, which depends on the coverage of C and W in time; p(C) and p(W) are introduced to guarantee the consistency between the ordinal temperature anomaly, TA_- and TA_+, and the reconstructed climate indicator C and W. It is usually a function of C (or W) and can be derived from observational data by regressing the relevant TA_- or (TA_+) on the C (or W) climate indicator series. The climate index, IC (or IW), is negatively (positively) correlated to the M year mean temperature, $\bar{T}$. For example, a larger IC in winter implies a more frequent occurrence of cold winters and/or more extremely cold winters and thus a lower $\bar{T}$, and vice versa. Finally, the temperature series on the scale $>M$ years can be deduced through a suitable calibration of the climate indices.

2.3. *Calibration*

The calibration relies on the relation between the M year mean temperature, $\bar{T}$, and the climate index, IC (or IW), defined by the ordinal temperature TA (see equation (5)). When both the warm and cold indices, IW and IC, are considered, their relation to the mean temperature, $\bar{T}$, is:

$$\bar{T} = a \times \mathrm{IW} + b \times \mathrm{IC} + c \tag{6}$$

where a, b, and c are parameters estimated from observational data. However, for special periods in history (e.g. the last 500 years) with fewer records and/or less precise descriptions about warm events (that is when the cold conditions prevail), the consideration of IC alone appears to be sufficient for the temperature reconstruction (Wang and Wang, 1988, 1989), while for other periods, the warm or both the warm and the cold climate index need to be considered.

Note that the regression between the mean temperature, $\bar{T}$, and the climate index IC or IW depends on the choice of the ordinal scaling parameter, σ, in equation (2), which is generally taken as the standard deviation of the observational temperature, T, as well as the resolution, M, in equation (5). Variable M should be chosen such that a reliable and stable relation between TA and IC (or IW) in equation (5) can be established. For the last 500-year climate reconstruction, we chose $M = 10$ years (section 3.2). By using a larger M, the series could be dated back to earlier epochs, say a further 2000 years, when the records were not as sufficient and detailed as those of last 500 years.

In the following, only the cold index, IC, series is constructed. The observational data at Shanghai station during the recent 110 years (1870–1979) serve as reference to deduce the calibration with $\sigma = 0{\cdot}7$°C (1·0°C) for summer (winter). Furthermore, a good correlation exists between the $M = 10$-year mean temperature $\bar{T}$ and the cold climate index IC ($r = -0{\cdot}867$). The regression coefficient is $-0{\cdot}2$ (see Figure 1), which means that an increase of the index IC by 1 is equivalent to a decrease of $\bar{T}$ by about 0·2°C (Wang and Wang, 1989).

3. APPLICATION: RECONSTRUCTION OF TEMPERATURE FOR THE LAST 500 YEARS IN SOUTH-EAST CHINA

The last 500 years are covered by the local chronicle period (1400–1900) as defined by Chu (1973), a period often considered as the main phase of the Little Ice Age (Lamb, 1977). In this period, local chronicles and documents were kept widely over China, especially in the eastern part of the country. A huge amount of written records about extreme weather and climate and the associated natural phenomena and agricultural damage are available to be used as indicators of temperature anomalies. The ones used for the reconstruction in this study are freezing of rivers and lakes, heavy snow, frost, heavy rain, and the duration of overcast skies (Table I). These phenomena are very sensitive to temperature changes, and provide a more objective judgement about the degree of coldness than descriptions such as 'winter is very cold', etc.

3.1. Climatological setting

The data in the following discussion were collected from south-east China, roughly covering the area between 24°N and 35°N and to the east of 112°E. According to climate classifications, this region belongs to the subtropical zone (Domrös and Peng, 1988). The 30-year (1951–1980) mean temperatures in April, July, and October are about 16°C, 28°C, and 18°C, respectively, with little difference from the north to the south. The 30-year mean January temperature is generally about 3–5°C. However, the difference, ranging from 0°C in the north of the region to over 10°C in the south (Figure 2), is considerable, which means that the intensity of the indicators may be different in different places for the same temperature anomaly in the whole region. In other words, a consistent prescription for evaluating the variables over the whole region is not possible. For the sake of convenience, the area under consideration is divided into three subregions, namely the Huai River basin around 33°N, the Yangtze River basin around 30°N, and the southern part of the region around 28°N, which are denoted as regions I, II, and III, respectively (Figure 2), each possessing roughly the same prescription for evaluating the VRs following the principles described in section 2.1.

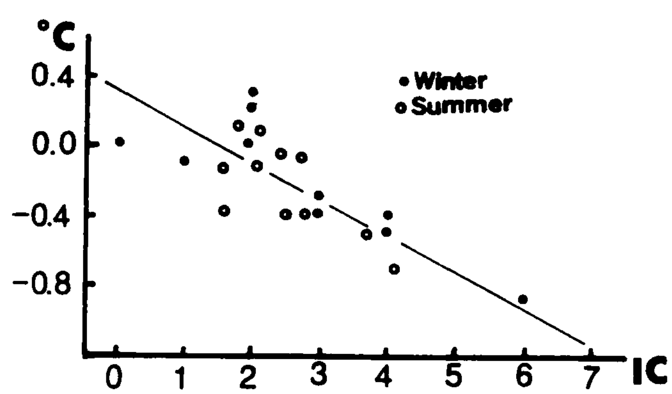

Figure 1. Scatter diagram for the 10-year mean temperature, $\bar{T}$ and the corresponding cold climate index (IC) in summer and winter

Table I. The indicators used as variables of reconstruction (VR)

	VR_1	VR_2	VR_3	VR_4	VR_5	VR_6
Winter	Freeze-up of rivers and lakes	Heavy snow	Frost	Date of first frost	Date of last frost	Miscellaneous
Spring	Freezing events	Snow	Frost	Date of last frost	Heavy rain and long duration of overcast skies in later spring	Miscellaneous
Summer	Frost	Snow	Heavy rain and long duration of overcast skies	Date of first frost	Date of last frost	Miscellaneous
Autumn	Freezing events	Snow	Frost	Date of first frost	Heavy rain and long duration of overcast skies in early autumn	Miscellaneous

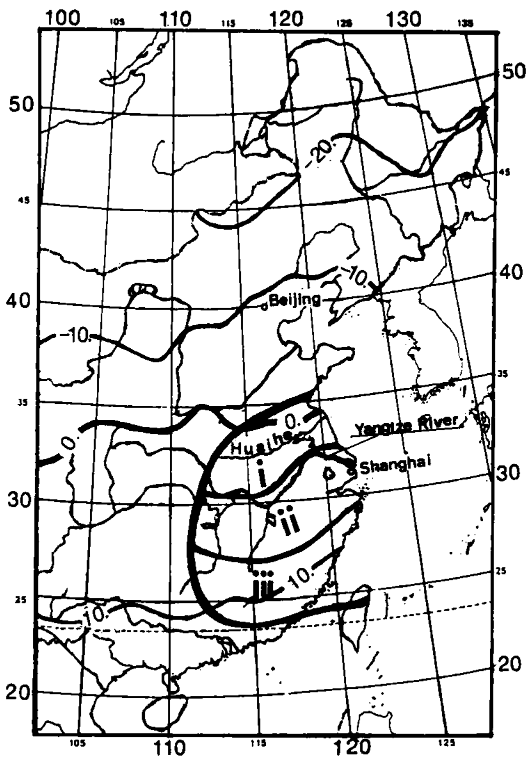

Figure 2. 30-year (1951–80) mean January temperature and the regions (I, II, III) covered by historical data used in this study

The reasons for the choice of this particular area for this study lie not only in its abundance of historical records, particularly during the last 500 years, but also in its crucial position, where the occurrences of the phenomena being used as indicators, such as freezing of lakes and rivers and heavy snows, are not too frequent to be regarded as events not worthy of notification, yet not too rare to be unable to construct a coherent time series relevant to the measurements.

The recent decades recorded the two coldest winters in this century: one was in 1955 when the Huaihe River froze up for 24 days, which is unique in this century, and the Tungting Lake (in region II) froze for 3 days; the

Table II. Ordinal values (grades) for the freezing up of rivers and lakes in winter

Value (in grades)	Region	Description
0		No record of freeze-up events
1	I	Huaihe frozen up
	II	Freezing of lakes occurred (with ice covering the lakes for few days)
	III	Water frozen on the ground
2	I	Huaihe frozen up for nearly a month, people could walk on the ice cover; small rivers frozen up for over a month
	II	Lakes and rivers frozen up for over 10 days, people walked on the ice cover
	III	Freezing of water in river caused the death of fishes
3	I	Huaihe frozen up for over a month, heavy cart moved on the ice cover as it would on the ground.
	II	Lakes and rivers frozen up for about a month, the ice cover could bear horse-drawn carts
	III	Freeze-up of rivers occurred, people could walk on the ice cover

other was in 1977 when some rivers and lakes in region II were reported to be frozen for some days (Feng *et al.*, 1985). The freezing variable takes the value of 1 in both cases according to Table II. Both freezing events were accompanied by heavy snow, which brought damage to agriculture and industry. The snow variable takes the value of 2 in both years. The temperature anomalies over the whole region in both winters were about −2°C. There are also reports about the occurrence of freezing and snow in 1957 and 1969 in regions I and II, though with less intensity (Feng *et al.*, 1985). The winter temperature anomaly in these two years was about 1°C below average. However, there are many records about more intensive cases in the last 500 years that were no doubt related to lower temperature records, such as in Shanghai (31·1°N, 121·3°E) in 1501, 'the lake and the river froze up for a month', Suzhou (31·3°N, 120·6°E) in 1654 'Taihu (lake) froze up for 20 days with 2 chi (roughly 60 cm) of ice cover', Shanghai in 1892 'extraordinarily cold, rivers and lakes froze up for over half a month', etc. Thus, the freezing events take the first priority for winter temperature reconstruction. Table II gives the specification for evaluating the Freeze-up events (VR_1). Considering that there are also some records, if not many, of freezing events that fell in spring and autumn, we put the freezing events into the catalogue of variables for temperature reconstruction of the corresponding seasons (Table I). For a given season and place, the intensity of freezing, which is reflected by the duration of freeze-up and the thickness of ice cover, was considered in evaluating the freeze-up events.

Extremely heavy snow, such as 'Snowing for over a month', 'deep snow without melting away until next spring', 'heavy snow crashing down houses, damaging trees or causing death to countless wild animals and birds everywhere and even to people', etc., which appears quite frequently in historical records of the last 500 years, is not to be found in those of recent decades, and the snow, especially in regions II and III, according to recent observation usually falls with a mixture of rain and melts away soon after it reaches the ground, which is called 'snow-rain' in Chinese. Less intense snows have occurred, however, for example in 1956, 1961, 1967, 1972, and 1974, with temperature anomalies around −0·5 to −1·0°C. There are also records about snow in spring and autumn and even in summer in the last 500 years. Therefore, snow is one of the variables to be considered in all seasons. In evaluating, considerations are made of the intensity indicated by duration of snowfall or frequencies of heavy snow in a given season, thickness of snowfall, and the effect on animals, as well as the time it took to melt away.

The first and last frosts define a measure for the length of the growing season, which is related naturally to temperature. The changes of average dates of first and last frosts in a given region indicate a shift of climate zones, which is an indicator of temperature change in all seasons, not only in the season in which they occur. However, because only the average dates are important in indicating the climate zone, they bear a relatively small weight for reconstructing the C series defined in equation (4) for individual years. According to the observation of recent decades, the average dates of first frost run from about the middle of November in region I to the end of December in region III, while those of last frost range between the end of March and the middle of February with extremes of about 2 weeks' departure from the average in both cases. The date of first (latest) frost and temperature are positively (negatively) correlated (Wang and Wang, 1988). In addition, there are many records about frosts that occurred in the months of winter, spring, and autumn, such as frost 'for many days' or 'consecutive tens of days, with trees being broken and crops damaged', etc. These should be considered separately from the dates of first and last frosts. There are also records of frost in summer, which is an event considered to be unusual at present even in North China. Therefore frost as a variable for reconstruction appears in all seasons. In evaluating the variables for frost, the intensity represented by the frequency of its occurrence in a given season and its duration for each occurrence and the corresponding agricultural damages are considered. The dates of first and last frost serve as another variable, the value of which depends on how far they depart from the average of recent observations.

Summer temperatures in China are significantly correlated with rainfall (Wang and Wang, 1988), as the latter is usually linked with cold air incursions. Furthermore, overcast skies during the rainy season are also a factor of summer temperature reduction, depending on the duration of the overcast. Extremely long overcast in the early half of autumn and later half of spring may also reduce the corresponding seasonal temperatures. Therefore, rainfall is considered in summer and partially in spring and autumn.

Finally, we have a large miscellaneous category. It includes various kinds of records that are not covered by any of the above-mentioned catalogue of variables. This is attributable to either the extreme rarity of the records or the difficulties encountered in evaluation of the record itself, such as records about the impact on animals, the damage to agriculture, and the content of descriptive expressions, for example, 'summer is very cold, old people must stay at home by fire to make themselves warm', or 'people must wear warm clothes', or 'winter is bitterly cold'. Although they directly reflect the climatic conditions at that time, care had to be taken in evaluating the variables, for the written descriptions are very likely subject to human bias. This category is only used for reference and further control.

3.2. Reconstruction of the cold climate index series

Based on the above discussion, we decided to use the variables listed in Table I. Following the procedure presented in section 2, the prescriptions or specific principles for evaluation of each of the variables (VR (k)) were defined according to the scaling principle given in equation (1). An example of this specification is shown in Table II for the freeze-up events in winter. In this way the relevant historical data were coded into numbers and stored in the form described in section 2.1 in order to obtain a consistent series for each climate indicator. Next, a combination of the relevant series (according to equation (4b)) leads to the C series for each of the four seasons, where the coefficients of the variables (see Table III) were obtained by comparison of the temperature anomalies in the relevant years using recent observations. Thus by comparing the winter temperature anomalies in 1955, 1977 when $VR_1 = 1$, $VR_2 = 2$, and other years when $VR_1 = 0$, $VR_2 = 1$, such as 1957, 1969, 1972, etc., the conclusion of $VR_1 : VR_2 = 2:1$ was drawn (Wang and Wang, 1989). The same holds for other seasons regarding their corresponding variables (compare Table I and Table III). For the variables that did not appear in recent decades, such as VR_1 of spring and autumn, VR_1 and VR_2 in summer, we take the coefficients of double amplitudes. Table III reflects the fact that the climate conditions indicated by freezing events are generally colder than those indicated by snow or frost for the same value of the corresponding VRs,

Table III. Coefficients of the variables used in Table I

	b_1	b_2	b_3	b_4	b_5	b_6
Winter	2	1	0.5	0.5	0.5	
Spring	2	1	1	0.5	0.5	
Summer	2	2	1	0.5	0.5	
Autumn	2	1	1	0.5	0.5	

which also agrees with the statistical fact that the occurrences of snow and frost are more frequent than those of freeze-up events, according to historical data as well as recent observations.

The series of the cold climate index (IC) for each season was derived from equation (5b) and shown in Figure 4. Here we set p (C) = constant, with values for spring, summer, autumn, and winter taken to be 1·0, 1·0, 1·0, and 0·5, respectively; derived from equation (4b) by the regression with recent observations. In this way we can use the universal calibration obtained from the measurement of the last 110 years in Shanghai, i.e. the coefficient $b = -0{\cdot}2$ for every season in this paper (see equation (6)), as shown by the example of summer and winter cases in Figure 1. The significant correlations of temperature between Shanghai and other stations over the region (see Figure 3) guarantee the reliability of the calibration using a single station for the whole region under consideration.

Moreover, we took one of the coldest decades, 1651–1660, as a case study to control the calibration. During this decade, the freeze-up of rivers and lakes in winter took place in 5 years, including 1651, when rivers in Zhenjiang prefecture (32·2°N, 119·4°E) froze up for 40 days, 1654, when Lake Taihu (31·2°N, 120·2°E) froze up for 20 days with ice cover of 2 chi (66 cm), and even the seashore in Haiyan county (30·5°N, 120·9°E) was frozen up, 1655, when the river in Putian County (25·4°N, 119·0°E) froze up and people could walk on the ice cover, and two other years (1653 and 1656) with less intense freezing. There are also records about heavy snow in 1650, 1653, 1654, 1655, 1656, 1658, and 1669, of which the most severe cases were in 1653, 1655, and 1656, when the records show 'the snow lasted for over 40 days in Yangzhou' and 'the snow cover in Longyan (25·2°N, 117·0°E) reached 3 chi (100 cm) remaining unmelted for about 10 days' etc. Through examination of the recent 30 years (section 3.1) and the present climate zone for which the above mentioned events are typical, the conclusion can be drawn that the temperature in winter at that time was lower than present by at least about 3°C. This agrees with the calibration shown in Figure 4. The same holds for the other seasons.

3.3. *Climate variations during the last 500 years*

The constructed climate indices are calibrated through equation (6) by taking $b = -0{\cdot}2$, $c = 0$ and without consideration of the warm events, and the result is shown in Figure 4. The changes in temperature of the last 510 years, that is 51 decades from 1470 to 1979, are characterized by both long and short-term fluctuations with some differences from season to season. The winter temperature variations bear a remarkable

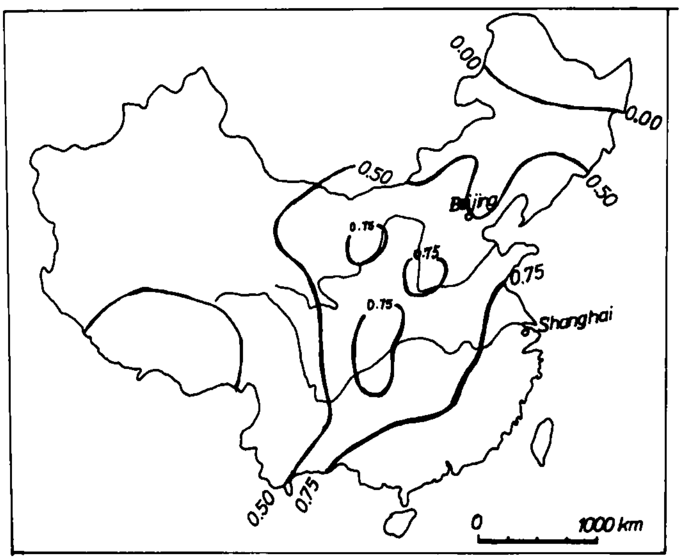

Figure 3. Distribution of winter temperature correlation between Shanghai and other 100 stations over China derived from recent 30-year (1951–1980) observations

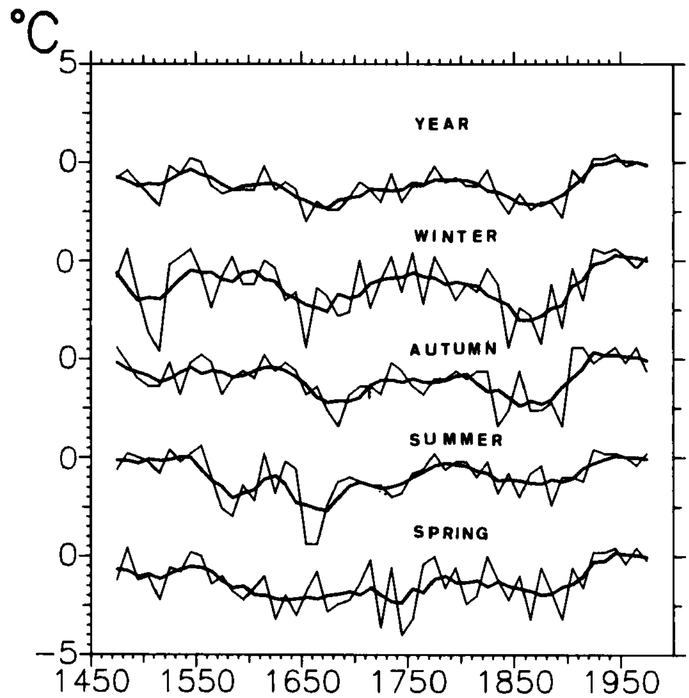

Figure 4. Temperatures for last 500 years derived from the cold climate index and the 5-decade running mean (thick lines)

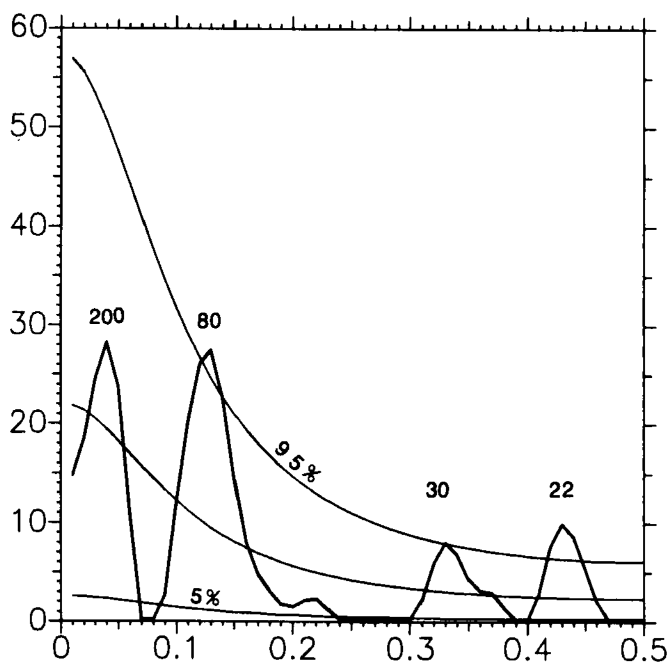

Figure 5. Spectrum analysis of the reconstructed series (Figure 4, year) with 51 decades and maximum lag of 30 decades. The 95 per cent as well as 5 per cent confidence levels are given

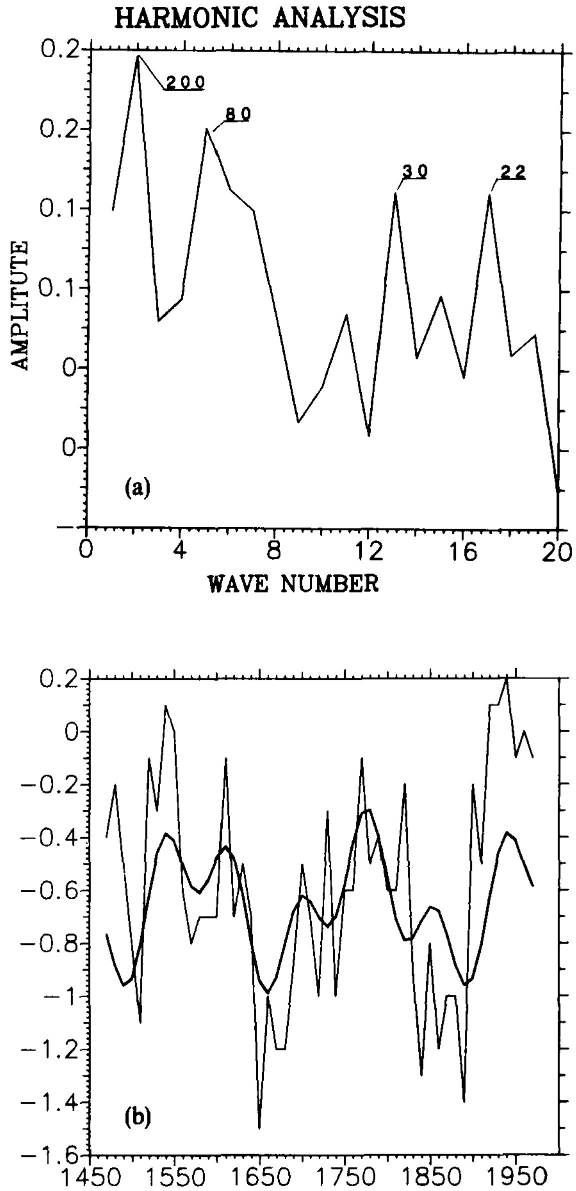

Figure 6. (a) Harmonic analysis of 40 data points isolating the 200-year and 80-year cycles (see Figure 5). (b) The original time series compared with the 200-year, plus 80-year harmonics

resemblance to the autumn temperature, while the summer and spring series demonstrate some kind of similarity. Furthermore, the cold phases in winter and summer generally precede those in autumn and spring by about two decades.

The annual mean temperature is taken as the average over the four seasons. It displays features similar to the winter and autumn. Three major cold periods, around the mid-fifteenth, the mid-seventeenth, and the mid-eighteenth centuries, are distinguished in Figure 4, which is in agreement with the results of Chu (1973) (see also Domrös and Peng, 1988). These fluctuations are dominated by periods of 200 and 80 years, as shown by power spectrum analysis (Figure 5). Harmonic analysis and the time series composed of these two modes (Figure 6(a and b)) show that they contribute most of the variance of the reconstructed temperature series. In addition, a 30-year and 22-year cycle are also detected, but this result has to be treated with caution owing to the decadal resolution ($M = 10$ years) of the time series. Note that the 80, 31, and 23-year cycles reach (and exceed) the 95 per cent significance level; the gap between the 80-year and the longer (200 year) period fluctuations is significant (lying below the 5 per cent level).

Another interesting feature of the last 500 years climate is the increase of temperature in the recent century. The coldest epoch during the last 500 years is around 1650, the next coldest one is at the end of last century while the warmest epoch is from the 1920s to the 1940s, which is warmer than the warmest period in history around the 1550s (Figures 4 and 6(b)). This increase in temperature during the recent century is most strikingly shown (Figure 6(b)) by the difference between the temperature and the curve fitted with two dominant harmonics (the 200 and 80-year fluctuations).

4. CONCLUSION

The application of the method in section 2 in the reconstruction of temperatures for the last 500 years from historical records in China provided a possibility to study the past climate on a quantitative basis. The climate changes in the last 500 years, which cover the main phase of the Little Ice Age, are characterized by a 200-year and an 80-year cycle; significant 22-year and 30-year fluctuations are also detected. The recent increase in temperature is also shown by the reconstruction. It is intended to extend the application of this method to reconstruct temperatures over longer periods in China, keeping the resolution M moderate and using more indicators.

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REFERENCES

Chu, K. C. 1936. 'Meteorological records of Beijing in Qing Dynasty', In: *Collected Papers of Chu Kochen, 1979*, Science Press, Beijing, pp. 214–216.

Chu, K. C. 1973. 'A preliminary study on the climatic fluctuation during the last 5000 years in China', *Scientia Sinica (B)*, **16**, pp. 226–256.

Domrös, M. and Peng, G. B. 1988. *The Climate of China*, Springer-Verlag, Berlin, 360 pp.

Feng, P. Z. *et al.* 1985. *Weather Calamities in China: 1951–1980*, China Meteorological Press (in Chinese).

Hu, H. H. 1944. 'Climate changes and a study of the climatic conditions of the Yin Dynasty', *Bull. Chinese Stud.*, **4**, 1–84.

Ingram, M. J., Farmer, G. and Wigley, T. M. L. 1981. 'Past climates and their impact on man: a review', In: Wigley, T. M. L. *et al.* (eds) *Climate and History*, Cambridge University Press, Cambridge, pp. 3–50.

Ingram, M. J., Underhill, D. J. and Farmer, G. 1981. 'The use of documentary sources for the study of past climates', In *Climate and History*, Wigley, T. M. L. *et al.* (eds), Cambridge University Press, Cambridge, pp. 180–213.

Lamb, H. H. 1977. *Climate: Present, Past and Future*, Part 2, Methuen, London, 835 pp.

Meteorological Center of Beijing (eds) 1982. *Data of Temperature Grades in China: 1911–1980*, China Meteorological Press (in Chinese).

Meteorological Bureaus of Shanghai, Jiangsu and others (eds) 1978. *Data of Historical Climate over East China During the Recent 500 Years* (in Chinese).

Pfister, C. 1981. 'An analysis of the little ice age climate in Switzerland and its consequences for agricultural production', in Wigley, T. M. L. *et al.* (eds) *Climate and History*, Cambridge University Press, pp. 214–248.

Wang, P. K. 1980. 'Meteorological records from ancient chronicles of China', *Bull. Am. Meteorol. Soc.*, **60**, 313–318.

Wang, P. K. and Zhang, D. E. 1988. 'An introduction to some historical governmental weather records of China', *Bull. Am. Meteorol. Soc.* **69**, 753–758.

Wang, S. W. and Wang, R. S. 1988. 'Reconstruction of summer temperature in China using historical documents', in *Collected Papers to the Honour of Professor Yao Chensheng for the Anniversary of his 50 Years Teaching*, Nanjing University Press, Nanjing (in Chinese).

Wang, R. S. and Wang, S. W. 1989. 'Reconstruction of winter temperature in China for the last 500 years', *Acta Meteorol. Sinica*, **3**(3), 279–289.

Wang, S. W. and Zhao, Z. C. 1981. 'Drought and floods in China', in Wigley, T. M. L. *et al.* (eds) *Climate and History*, Cambridge University Press, Cambridge, pp. 271–288.

Zhang, D. E. 1980. Winter temperature changes during the past 500 years in South China. *Kexue Tongbao, No.* 6.