RECONSTRUCTING MIDDLE-TIBET CLIMATE DURING THE LAST 600 YEARS BY DENDRO-CLIMATOLOGICAL METHOD*

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ABSTRACT

Based on four tree-ring chronologies which was analysed with appropriate collection and accurate dating in the middle Tibetan Plateau, an essential procedure on reconstruction of past climate has been pointed out in this paper. First, the response function of each dendrochronology has been built and used to estimate how ring-width growth responds to variations in monthly climatic change. Second, the climate factors which could be produced with different tree-ring series have been selected. Then, the transfer function equation, including a new set of orthogonal variables, can be used to reconstruct local past temperature or precipitation. It should be emphasized that prior growth has been considered in the relationship between climate factor and tree-ring chronology, Besides, some different periods for calibration and verification have been divided. And some statistics and other kinds of proxy data have been adopted as test approaches. As a result, the variations of air temperature during the last 600 years and precipitation during the last 340 years were reconstructed by combining the same types of tree-ring series in the middle Tibet.

I. INTRODUCTION

It is no doubt that the variation of tree-ring width which responds to local climatic change can be used to estimate the variation of climate factor. As proxy data which may be assigned accurately to a particular year and place, tree-ring chronology has become one of major approaches widely used to study the climate change during Historical Time in the world.

In China, dendroclimatic work which may derive the variation of local past temperature and/or precipitation began in the 1930s, but the systematic study on dendroclimatology has improved during recent 10 years and more. Especially, there has been striking advances in the field of tree-ring analysis for reconstructing past climatic factors of air temperature, precipitation and sea-level pressure during the last years (Wu and Lough, 1987; Wu et al., 1988). In order to yield reliable and advantageous tree-ring chronologies, Wu et al. (1988) have demonstrated the "three-step dating" method as an effective approach to do crossdating. It should be noted that four final tree-ring chronologies located in the middle Tibet were established. Among them, two are located in Nyingchi County; the others are in Mainling County and Lhünzhub County, respectively. These chonologies are individually named (NYI) 1, (NYI)2, (MAI) 1 and (LHU) 1. The data sets can be basically put into two categories. One is near the upper limits of forests with high altitude. The other is from arid area of lower altitude.

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The details of the sampling sites, including the latitude, Longtitude, altitude and others, are listed in Table 1.

Table 1. Summary of Four Tree-Ring Chronologies in Tibet (June—July, 1985)

I. D.	(NYI) 1	(NYI) 2	(MAI) 1	(LHU) 1
Site	Bajie, Nyingchi	Shejinashan, Nyingchi	By the Yarlung Zangbo River	Rezhen Temple, Lhünzhub
Lat. (N)	29°42′	29°44′	29°12′	30°14′
Long. (E)	94°13′	91°33′—35′	93°34′—37′	91°22′
Elevn. (m)	3145	4500	3150	4320
Direction	S	SSE	N	SE
Slope (degree)	20—25	35—37	15—25	5—10
Species	Cypressus gigantea	Sabina saltuaria	Pinus densata	Sabina wallichiana
Number of cores	28	42	30	28
Life time (Yr.)	1618—1984	1380—1984	1741—1984	1593—1984

It should be emphasized that these four ring-width chronologies have been from typical environment with effective sampling, measuring, dating and curve fitting. Thus, they are reliable final chronologies for reconstructing the past climate in the middle part of Tibet.

II. ESTABLISHMENT OF RESPONSE FUNCTION

In dendroclimatology, response function has been widely used to estimate how ring-width growth responds to variations in monthly climatic conditions. It is necessary to be established before reconstructing past climate. Fritts and Wu (1986) analysed three different response-function programs. The results were described and compared one to another as well as to those obtained from some other regression methods. Also, the rationale for the different response-function solutions was discussed. The details of method and calculation of response function are not necessary to be described in this paper.

Here, several key steps concerned with the mid-Tibet dendrochronologies will be mentioned. One of them is about the selection of near meteorological station as basic reference point. It is sure that the Nyingchi Meteorological Station which is the nearest one to both sites of (NYI) 1 and (NYI) 2, 5 km and 30 km distant from them respectively, can be considered as a reference point. Sometimes, it is not easy to find appropriate stations as such points because of the lack of observation data in Tibet. For (LHU) 1, there is no meteorological station in this county. The nearest station is in Damxung County, but there is a huge body of the Nyainqentanglha Range between the station and the tree-ring site. Of course, the station can not be as reference point for (NYI) 1 because of different climate types. Fortunately, we found that Lhasa Meteorological Station, which is about 120 km distant from the tree site, could be used as a reference point. As a special case, (MAI) 1 is located on the south bank of the Yarlung Zangbo River. There are a couple of meteorological stations near the tree site, but the observed records only less than 20 years, which is not enough to calculate the stable response function. Actually, we could not find any meteorological stations as the reference point. As a result, the response function of (MAI) 1 has not been analysed in this paper.

Another key step is about the determination of climate factor number, which is concerned with the length of observed record. It can be adopted for Lhasa Station to select monthly mean air temperature and total precipitation for 12 months starting with October of the last year because its length of successive observed record is more than 30 years. Together with three prior growing factors, the total predictors amount to 27. Similarly, eight-month length is selected for Nyingchi Station because it has only 25-year data. In order to keep the influence of prior winter, the first month in response function equation starts with January. The total predictors must be 19.

By carrying out analysis of an orthogonal transformation and all-step multiple regression on the tree-ring chronology the response function for chronology (NYI) 1 with Nyingchi climatic data has been derived and shown in Fig. 1. All of the eigenvectors (100%) were included as the initial regression in each program. The vertical lines designate the 0.95 confidence ranges. And the significant elements were marked with "*" in the figure.

According to the response function, a positive response of (NYI) 1 to some-month temperature can be seen. The significant factors suggest that high temperature in January and July would be of benefit to nutrition-material accumulation and cambium activity of these trees at the site. However, the high temperature in June, which is related with starting of rain season, may be caused by less precipitation. Thus it could lead to the excessive expense of nutrition material in tree and limited tree growth, hence, the significantly negative response to June temperature for (NYI) 1.

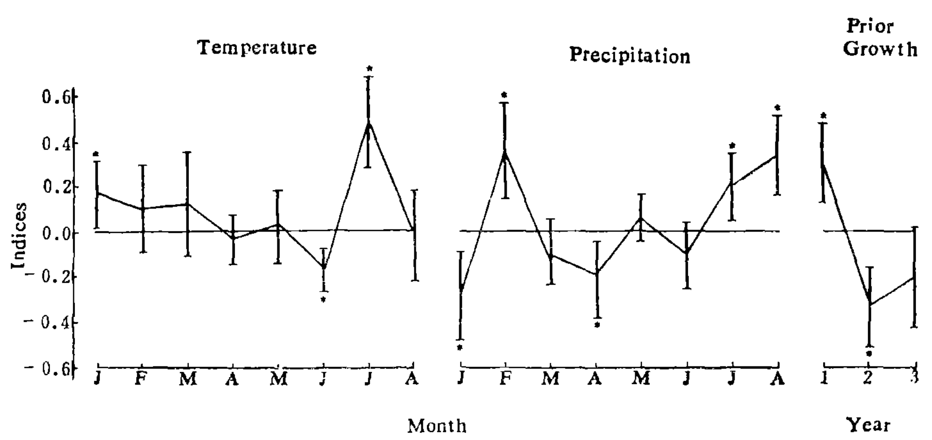

Fig. 1. Response function of (NYI) 1.

The response to rainfall in Fig. 1 portrays that five of all eight factors are significant. The main feature of response is negative during the prior period of growing season; and it is positive during the growing season, especially in July and August. It demonstrates that more rainfall during growing season must be helpful to tree growth in such arid area. The relationship between climate and tree growth for (NYI) 1 is basically in accord with that for most dendrochronologies in arid area. As for prior growth, both one-year and two-year lags are important for current year growth. The one-year lag seems positive response; and the two-year lag negative.

The multiple correlation coefficient (R) of final regression equation which contains 19

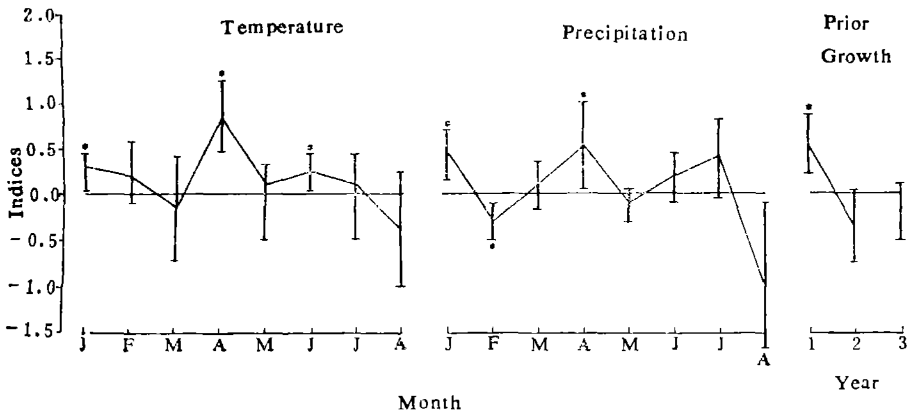

Fig. 2. Response function of (NYI) 2.

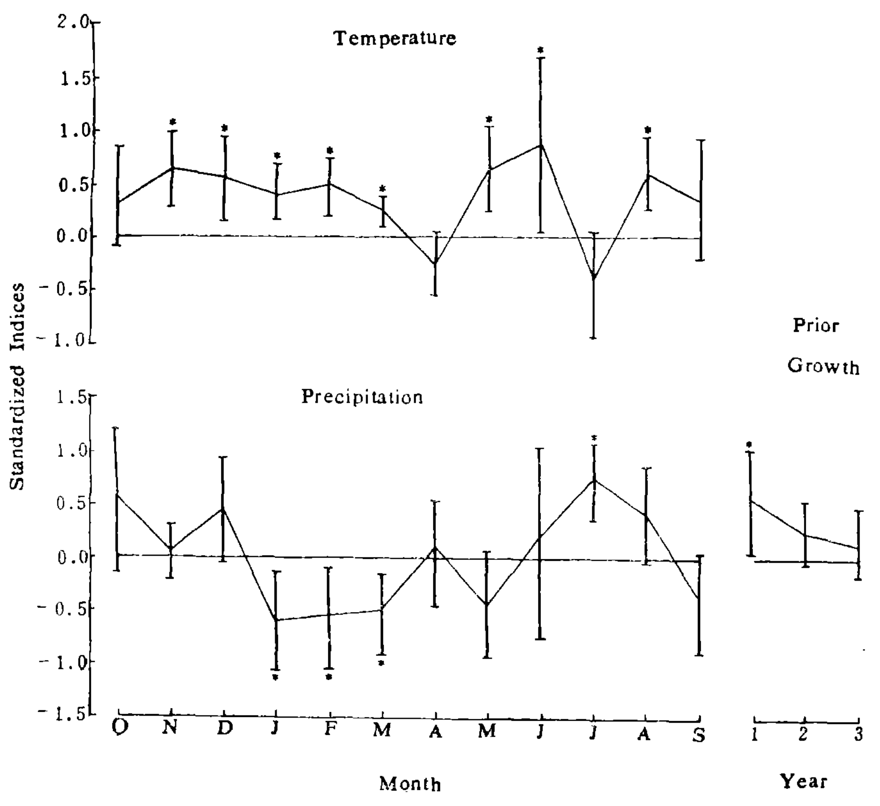

Fig. 3. Response funcion of (LHU) 1.

factors can reach 0.88. The variance explained by prior growth is 16.6%, by climatic factor is 60.1%, the total is 76.7%. It also shows that there is much valuable climate information in the chronology (NYI) 1. Taking three tree-ring chronologies as samples to compare with (NYI) 1, they are from the arid area of western America; two are in California and one in southern Arizona (Fritts and Wu, 1986). On an average, the variance for them explained by prior growth is 17.4%, which is a little bigger than that for (NYI) 1. Their averaged variance explained by climatic factor is 48.7%. It is lower than the variance for (NYI) 1. The total variance for three chronologies is also lower than that for (NYI) 1. It has been reported that the variance explained by climate for 102-site chronologies which can be used for reconstructing past local climate in western U.S. is about 60% (Graybill, 1982). This statistical result shows a criterion of good quality chronology. It is obvious that the chronology (NYI) 1 may belong to the same category and indicate the climatic change, especially the variation of local rainfall.

Other two response functions derived from (NYI) 2 and (LHU) 1 are shown in Figs. 2 and 3, respectively.

It is clear that their response values to air temperature seem to be positive in most months. The values appear negative in a few months, but they never reach the significant level. Especially, eight of all 12 months appear significant positive response for (LHU) 1. It is not easy to be seen for other timber line chronologies. As a result, both of them are sensitive to temperature variation. As for response to rainfall, they seem not similar each other because of different small growing sites. However, the positive response during the growing season to rainfall for them seems obvious. As for the response to prior growth, the one-year lag is significantly positive.

The multiple correlation coefficient (R) of the response regression for (NYI) 2 is 0.90, and 0.86 for (LHU) 1. The variances explained by climatic factor for them are 60% or so. Their total variances are 82% and 73%, respectively. The statistics for them are listed in Table 2.

Table 2. Statistics of Three Response Functions

Chronology	(NYI) 1	(NYI) 2	(LHU) 1
Variance (%)			
Prior growth	16.59	17.44	14.15
Climate	60.06	64.25	59.24
Total	76.65	81.69	73.39
Multiple R	0.876	0.904	0.857
Total factors	19	19	27
Significant elements	10	8	13

The analyses of establishing response function have demonstrated that these chronologies are positive in response to climate and coincident with biological theory of tree growth at these collection sites. Of course, it will be possible to use them for reconstruction of local climatic change.

III. RECONSTRUCTION OF CLIMATE FACTORS

As for climatic predictands, it can be carried out from the response function and relationship between chronology and climate. (NYI) 2 and (LHU) 1 were from timber line in Tibet. The variances explained by climate for them can reach 60%. The chronologies can be used for reconstructing past temperature variation. According to the distribution of significant elements, the spring season (April—June) may be the most active for growing in (NYI) 2 site. The correlation coefficient (r) between tree-ring index and spring temperature is 0.75, passing significance tests at the 95% confidence level. Thus, we will consider the April—June average temperature as the predictand for (NYI) 2. Similarly, we have found that the response to temperature might be more significant in either period, spring season or prior winter. By taking the prior October through September as a year, the correlation coefficient between ring index and year's temperature is 0.75. Of course, the predictand for (LHU) 1 could be determined.

(NYI) 1 belongs to another kind of chronology which was from lower tree line in arid area. Its variation is often concerned with rainfall variation. Based on its response function, the significantly positive value appeared in the growing season. The correlation coefficient between ring index and rainfall of May through August is 0.73. Of course, the precipitation from May through August is considered as the predictand for (NYI) 1.

As for (MAI) 1, it could not be analysed by response function because of shorter observed series. The chronology might be sensitive to rainfall due to collection site and relationship calculation. At last, the year's precipitation from prior October through September has been chosen as reconstructing predictand.

When the single chronology at one site is used for reconstructing past climate, the general transfer function is often derived from linear regression. The prior growth (one to three years' lag) will be included in the regression equation. In order to guarantee independence of all predictors in the equation, the empirical orthogonal function (EOF) has been adopted for transformation of predictors. Thus, the transfer function will be based on the regression equation including the departure of climate predictand and four independent predictors.

The different dependent calibration and independent verification periods can be selected in reconstruction process in terms of different length of observed meteorological data. The calibration period for chronology (LHU) 1 would be 25 years (1960—1984), and the verification 7 years (1953—1959). For (NYI) 1 and (NYI) 2, the calibration and verification would be 20 and 5 years, respectively. Considering the short observed data, all 17 years are considered as calibration.

All annual values, observed and reconstructed departures, have been drawn in Figs. 4 and 5. Both temperature and precipitation estimated values (broken line) derived from transfer equation are close to observed data (solid line). The deviation between observed data and estimated values for each tree-ring site has been given in Table 3. The averaged deviation (d) of air temperature is near 0.2°C. The larger d value of precipitation is only 40 mm and more. Especially, their trends of fluctuation for each site look like similar. It seems that the reconstructions are reliable.

Reduction of error (RE) is popularly adopted in verification test for dendroclimatic reconstructions. The statistic is a most rigorous test of the reliability of the estimated climate (Gordon, 1980). The RE statistic can range from $-\infty$ to a maximum value of 1.0. Generally, $RE > 0.3$ is often taken as a criterion to judge the reconstruction.

The calculated results have shown that every RE value from the comparison between actual data and calculated values far exceeds 0.3 for four tree-ring chronologies. The largest one reaches 0.76 (see Table 3). It also means that these reconstructions would be reliable.

We have also tried to find some local historical documents, in which severe cold or drought events have been recorded for the test of reconstruction. For example, it was anomalous cold in Lhasa in 1905 according to a former top officer to Tibet, You Tai's diary (Lin

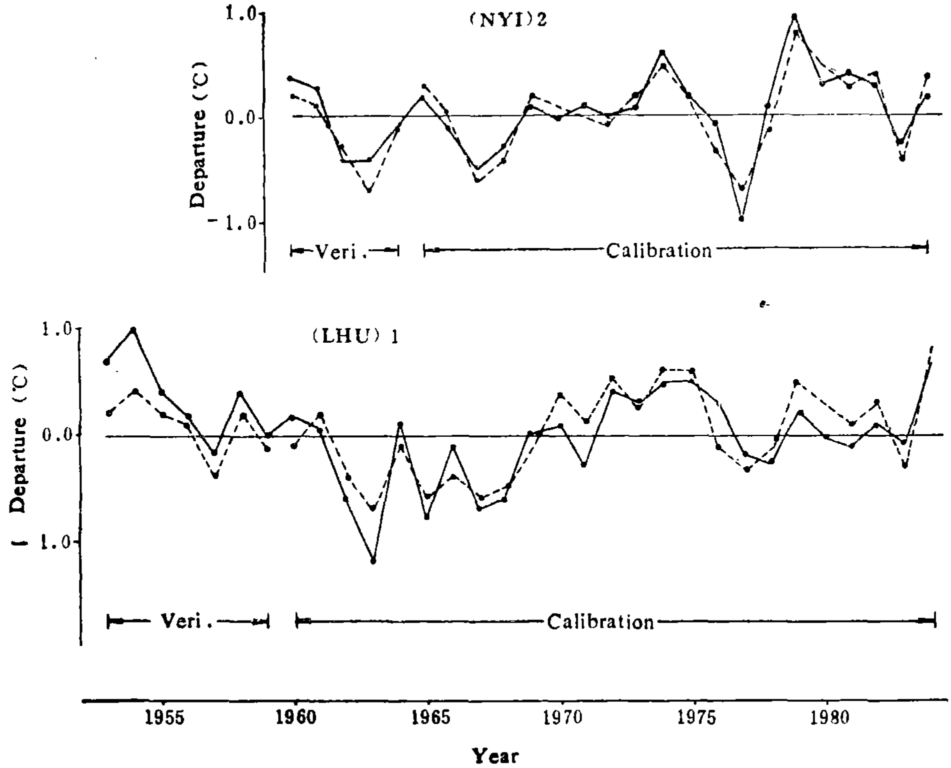

Fig. 4. Reconstructed temperature value.

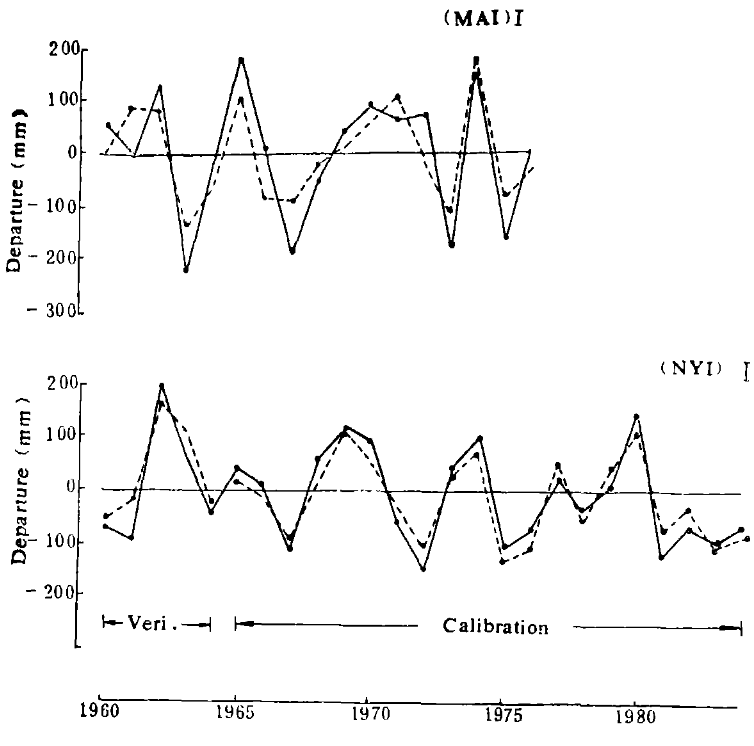

Fig. 5 Reconstructed precipitation value.

and Wu, 1984). At the same time, the reconstructed temperature departure was -1.1°C, which indicated a quite cold year of 1905. Another example is about drought. According to the Tibetan calendar in history file, an anomalous drought appeared in summer of 1937 around the middle Tibet area (Wu and Lin, 1987). The estimated precipitation values from (NYI) 1 and (MAI) 1 were large negative departures in 1937. In addition, there were some others, which are not necessary to be listed here.

Table 3. Statistics for Reconstruction

I.D.	(NYI) 1	(NYI) 2	(LHU) 1	(MAI) 1
Predictand	Precipitation in growing season	Temperature in spring	Annual temperature	Annual precipitation
r	0.731	0.750	0.752	0.801
d	23.7mm	0.17℃	0.22℃	43.3mm
RE	0.70	0.76	0.55	0.67
Calibration	1965—1984	1965—1984	1960—1984	1968—1984
Verification	1960—1964	1960—1964	1953—1959	……

IV. CLIMATIC CHANGE AND ITS FEATURES

By using the power spectrum analysis, some cycles have been derived from each tree-ring chronology (see Table 4).

In the four tree-ring chronologies, it is common to contain a cycle of 2 years or more, which closely coincides with the so-called "quasi-biennial pulse" in various meteorological records. This cycle could be concerned with the couple oscillation of air-sea interaction and may be the most distinct period except the annual cycle in most areas. As for other obvious cycles of 11 and 22 years, they could be concerned with the solar action and should be considered in long-term climatic change analysis. More cycles, including quasi-3, 5, 8, 30 and 80 years or more, are valuable for understanding the features of local climatic change.

Table 4. Some Cycles in Four Chronologies

quasi-cycles	2 years	11 years	22 years	others
(LHU) 1	2.1—2.3	10.3—10.9	22.3	3.4, 4.7—5.1, 8.5—8.6, 34.0, 78.0
(NYI) 2	2.0—2.3	10.4	21.7	5.2, 8.6—8.9, 70.9
(NYI) 1	2.0—2.1	12.3—12.6		5.6—5.8, 7.0—8.0, 80.0
(MAI) 1	2.0—2.1	12.0		3.5,5.1—5.7, 7.5—7.9, 65.0

The cross-spectrum analysis has been adopted in each two chronologies, indicating temperature and precipitation, respectively. While the major cycles in Table 4 are same for two chronologies, the calculated coherence values (Rh) are mostly more than the critical value (Rc). For example, when the common cycles for (LHU) 1 and (NYI) 2 were shown to be 2.1, 2.2 and 2.3 years, Rh values were equal to 0.919, 0.901 and 0.882, respectively; Rh=0.801, 0.881 and 0.871 with the common cycle being 10.4, 21.7 and 22.3 years, respectively, etc. All the Rh values were more than Rc=0.707 with the confidence level= 0.005. In many other cycles, the same situation happened. It is obvious that the close relationship between these chronologies at most spectra is really present. The analysis shows that the same conclusion can be derived for other chronologies, (NYI) 1 and (MAI) 1.

In order to describe the general pictures of climatic change in the middle Tibet, we need to make two curves which indicate annual mean temperature and annual precipitation. The regressive transformation has been adopted for combining two different types of climatic series, based on the great relationship proven by cross-spectrum analysis and the high correlation coefficients of 0.84 and 0.81 for temperature and precipitation, respectively. By carrying out low-pass filtering, two curves are shown in Figs. 6 and 7.

A trend curve of the annual air temperature variation during the last 600 years is illustrated in Fig. 6. It can be clearly seen that several cold and warm periods have appeared alternately since the late 14th century. The major warm periods cover the 16th century, the early 17th—early 18th century, the late 18th and 19th century, and most of the 20th century. The distinct cold periods appear in 1420s—1490s, 1630s—mid 1670s, 1760s—1780s, the early 19th century-mid 1850s and 1880s—1890s. The coldest one is around the mid 17th century, in which the departure of annual mean temperature reached −0.6°C or more. Since then, the trend has been to show the rising temperature. The departure during the last 30 odd years, averagely, was 0.16°C higher than the long-term mean value, and it seems to keep the warming trend. The frame of temperature variation in the middle Tibet has shown the same as the fluctuation in the whole Plateau (Wu and Lin, 1981), and it could be similar to the climatic change in the whole China concluded by Prof. Zhu (1973).

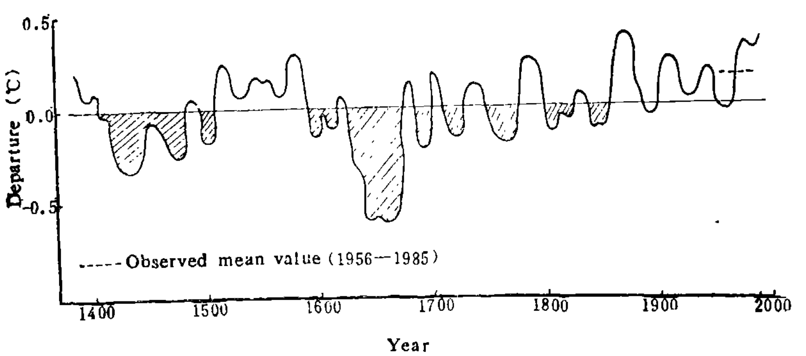

Fig. 6. Fluctuation of temperature in the middle Tibet.

As for precipitation, several different periods might be demonstrated during the last 340 years. The major wet period appeared from the mid 17th through the early 18th centuries. Another one, the end of 19th century to 1930s, might be a longer episode, too. The detail of precipitation fluctuation has been shown in Fig. 7. It should be emphasized that the middle Tibet has experienced dry period during the last 30 odd years and is facing the trend

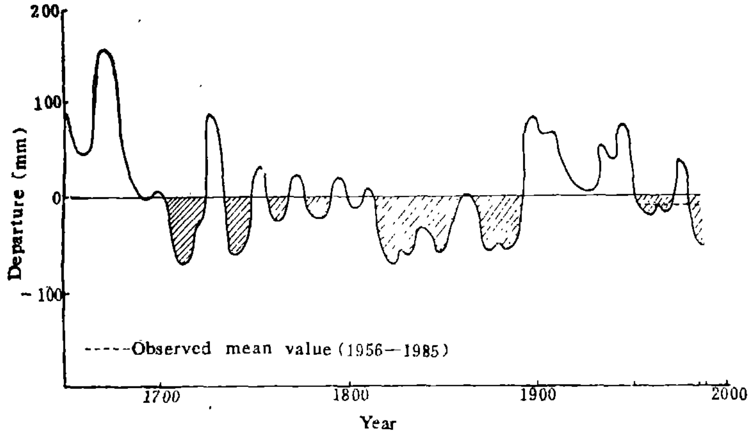

Fig. 7. Fluctuation of precipitation in the middle Tibet.

of keeping dry.

We need, of course, more data and analyses for understanding the more features on climatic change in the middle Tibet.

V. CONCLUSIONS

This study has demonstrated how to reconstruct past climatic change using four tree-ring chronologies in the middle Tibet Plateau. Some results could be summarazed as follows:

(1) By carrying out response function analysis, some response characteristics of tree-ring chronologies to climate have been estimated. They are coincident with biological theory of tree growth at collection sites and have demonstrated the possibility of reconstracting local climate.

(2) Prior growth and orthogonal transformation have been adopted in establishing transfer function. Both calibration and verification functions have been considered. All results have provided the reliability of reconstracting past temperature and precipitation in the middle Tibet.

(3) According to the fluctuation trend, the mid-Tibetan climate could be divided into some distinct cold/warm and dry/wet periods during the last hundreds of years. At present, it is in warm and dry period. Besides, some quasi-cycles on climatic change have exsisted.

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