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Response and dendroclimatic implications of δ^{13}C in tree rings to increasing drought on the northeastern Tibetan Plateau

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[1] The stable carbon isotope composition (δ^{13}C) of tree rings in a climate-sensitive region can provide a retrospective view of changes in environment and climate. Here, we report on the development of the first annually resolved δ^{13}C tree ring chronology obtained from natural forests on the northeastern Tibetan Plateau. Climate data show a warming trend and more frequent droughts occurring in the research region since the 1970s. The isotope record of Qinghai spruce (*Picea crassifolia*) spans the period 1890–2002 with a general decreasing trend over the last century followed by an abrupt increase in δ^{13}C over the last decade. The stable carbon discrimination against heavier atmospheric carbon (Δ^{13}C) is negatively correlated to May temperature and positively correlated with June–July precipitation. The regional Palmer drought severity index (PDSI) correlated significantly with Δ^{13}C series after 1960, whereas this relationship was not stable over the period 1933–1960. However, much stronger correlations were observed between the high-frequency anomalies in annual Δ^{13}C and PDSI in June and July during the period 1933–2002. The temporal stability analysis revealed trends in the response to drought stress affecting tree's Δ^{13}C linked to climatic warming. Intrinsic water-use efficiency increased by 7.7% in Qinghai spruce in response to increased severity of regional drought during the 1990s compared to the average of the previous decade. Our preliminary results suggest that carbon isotope in certain tree taxa growing on Tibetan Plateau may be an effective proxy for reconstructing regional drought.

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1. Introduction

[2] The $^{13}C/^{12}C$ isotope ratio in plant matter is determined by the stable carbon isotope composition (δ^{13}C) of atmospheric CO_2 [*Ainsworth and Long*, 2005] and by a number of environmental factors, e.g., temperature, precipitation, relative humidity, soil moisture, and nutrient availability [*Francey and Farquhar*, 1982; *Farquhar et al.*, 1982]. The atmospheric CO_2 concentration has increased since 1750, and about three-quarters of the anthropogenic emissions of CO_2 to the atmosphere is due to fossil fuel burning [*Stuiver and Braziunas*, 1987], resulting in a decreased trends of δ^{13}C atmospheric CO_2. Both affect the δ^{13}C ratio of plants because the carbon isotope composition of photosynthetically produced organic matter is determined by the δ^{13}C value of the atmospheric CO_2 and the leaf intercellular to atmospheric CO_2 concentration [*Farquhar et al.*, 1982]. Correlations with temperature have often been found in studies relating the δ^{13}C content of tree rings to climate [*Stuiver and Braziunas*, 1987; *Lipp et al.*, 1991], and many studies have shown that seasonal precipitation affects the δ^{13}C content of tree rings [*Robertson et al.*, 1997; *Treydte et al.*, 2001; *Liu et al.*, 2004, 2007a]. From a theoretical perspective [*Farquhar et al.*, 1982], humidity conditions and soil water content are expected to be important factors influencing the δ^{13}C content of tree rings, because water stress can induce closure of stomata and thus increase the proportion of δ^{13}C in the incorporated carbon [*Saurer and Siegenthaler*, 1989; *Dupouey et al.*, 1993; *Leavitt and Long*, 1988]. Both soil moisture and air relative humidity can influence δ^{13}C incorporation, but the reaction of plants to the two stress factors is not the same. Recent studies also highlighted the strong relationships between δ^{13}C in tree rings and regional drought events [*Leavitt et al.*, 2007; *Leavitt*, 2007].

[3] When considering the relationship between δ^{13}C in cellulose and meteorological parameters, the long-term effects of atmospheric CO_2 should be corrected by using equations which described in section 2.5 to obtain the carbon isotope discrimination (Δ^{13}C) series [*Treydte et al.*, 2001; *Liu et al.*, 2004; *McCarroll and Loader*, 2004]. *Francey et al.* [1999] have obtained a high-precision record

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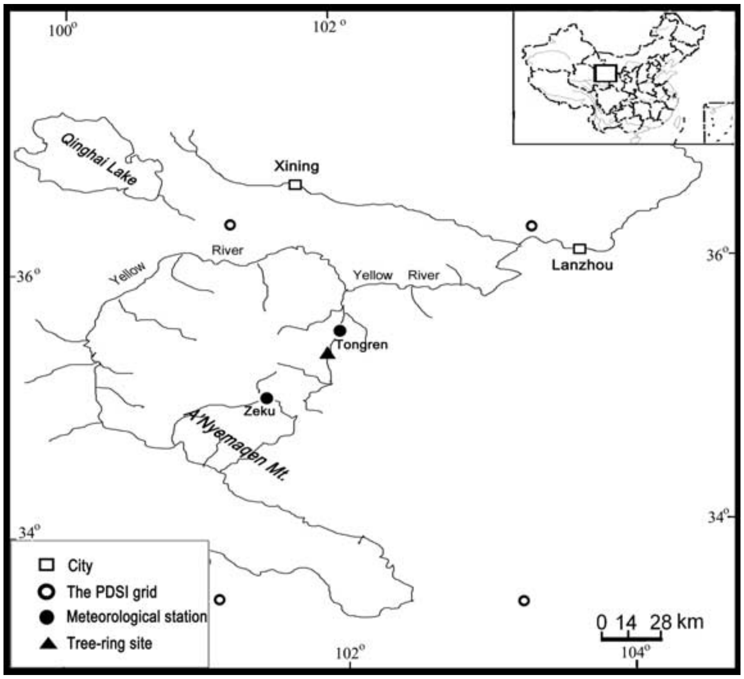

Figure 1. Map showing the sampling site. The nearby meteorological stations are shown.

of atmospheric δ^{13}C from Antarctic ice cores. Further, *McCarroll and Loader* [2004] used this record to estimate annual values of CO_2 concentration and δ^{13}C in air, and these yearly data are sufficiently precise to provide a standard method of removing the atmospheric decline in δ^{13}C from the tree ring data.

[4] Considerable complexity exists regarding the relationship between tree ring Δ^{13}C composition and climate, and thus an integrated environmental index is needed to explore further connections between Δ^{13}C and climatic parameters. The Palmer drought severity index (*PDSI* [*Palmer*, 1965]), which is used worldwide [*Cook et al.*, 1999; *Dai et al.*, 2004; *Zou et al.*, 2005; *D'Arrigo et al.*, 2006], was developed by *Palmer* [1965] as a means to measure moisture conditions by incorporating antecedent precipitation, soil moisture demand and supply into a primitive hydrological accounting system. The use of PDSI for drought reconstructions from tree ring widths in China is under investigation [*Li et al.*, 2007], and the reconstruction of drought history gives more information on climate change on temporal and spatial scales. Theory suggests that increased CO_2 should lead to a decrease in stomatal conductance and thus a decrease in isotopic discrimination [*Field et al.*, 1995]. A number of processes interact to modulate the regional evapotranspiration and dry matter accumulation to increased CO_2 [*Field et al.*, 1995; *Clifford et al.*, 1993]. Therefore the effects of rising CO_2 and water stress may impose together.

[5] With an average elevation above 4000 m a.s.l., the Tibetan Plateau (TP) is extremely sensitive to climate change [*Zheng*, 1996]. In such a remote region, studies of past climate must rely on proxy records such as tree rings and ice cores because instrumental records are generally short [*Bradley*, 2000; *Yao et al.*, 2002]. Dendroclimatological investigations on the TP started in the 1970s in China [*Wu and Lin*, 1978; *Wu et al.*, 1990], and have increased considerably over the last 10 years [*Bräuning and Mantwill*, 2004; *Helle et al.*, 2002; *Qin et al.*, 2003; *Zhang et al.*, 2003; *Shao et al.*, 2003, 2005; *Sheppard et al.*, 2004; *Gou et al.*, 2005, 2006; *Liang et al.*, 2006a, 2006b; *Liu et al.*, 2005, 2006, 2007a, 2007b]. However, most dendroclimatic studies have considered only the relationship between ring width and climate change. Little attention has been paid so far to the isotopic record in this region.

[6] The purpose of this study is to identify correlation between stable carbon isotopes in tree rings and environmental parameters, and to establish the feasibility of reconstructing the past response of δ^{13}C to drought in northeastern TP, China, with its complicated topography and variable climate due to high altitude and mountainous terrain. The objectives of this study were: (1) to examine the relationship between stable carbon discrimination (Δ^{13}C) in tree rings and climate parameters, including temperature, precipitation and relative humidity; and (2) to evaluate the long-term stability of the relation between Δ^{13}C and regional PDSI, and the response of tree growth to drought stress.

2. Materials and Methods

2.1. General Information About the Study Area

[7] The study area is located in a transitional region between the TP and the south-eastern Loess Plateau in Qinghai province, China. The climate on the TP is influenced primarily by Westerlies, and the East-Asia monsoon prevails on the Loess Plateau. The locations of the sampling site and nearby weather stations are shown in Figure 1. There are several mountain chains and rivers in the region. The elevation of the region is 2100–4700 m a.s.l., and the climate is characterized as cool and arid.

2.2. Climatic and PDSI Data

[8] The climate data used in this study include local meteorological records (i.e., temperature, precipitation and relative humidity) as well as the monthly PDSI data of

Table 1. Descriptions of the Tree Ring Site, Two Meteorological Stations and the Four Nearest PDSI Grid Point Developed by *Dai et al.* [2004]

Data Type	Site Code	Location (Latitude; Longitude)	Elevation, m a.s.l.	Time-Span, A.D.
Tree ring	Maixiu	35.27°N; 101.95°E	3400	1891–2002
Meteorological data	Tongren	35.52°N; 102°E	2487	1959–2002
	Zeku	35.03°N; 101.47°E	3655	1959–1992
PDSI	···	36.25°N; 101.25°E	···	1933–2002
	···	33.75°N; 101.25°E	···	1933–2002
	···	36.25°N; 103.25°E	···	1933–2002
	···	33.75°N; 103.25°E	···	1933–2002

four surrounding grid sites developed by *Dai et al.* [2004] (Table 1 and Figure 1). The PDSI data set developed by *Dai et al.* [2004] is available on a 2.5° × 2.5° grid. A given PDSI value reflects the progression of trends, whether it is a drought or a wet spell. That means that a single PDSI value is not representative of just the current conditions, but also of recent conditions to a certain extent. The negative and positive PDSI values indicate a drought and a wet spell, respectively [*Dai et al.*, 2004].

[9] The local instrumental data were obtained from two nearby meteorological stations (Tongren and Zeku; Figure 1 and Table 2); the Tongren station (35°31′N, 102°E, 2487 m elevation, periods of records, 1959–1984 and 1991–2003) and the Zeku station (35°02′N, 101°28′E, 3655 m elevation, period of record 1959–1992), which provide the meteorological data, are located about 60 km northeast and southwest of the sampling site, respectively (Figure 1). It should be noted that the Zeku station was closed after 1992, so there are no records thereafter.

[10] The average correlation of paired temperature and precipitation series of corresponding months at the two stations are 0.991 (n = 324) and 0.899 (n = 312), indicating a coherent regional climatic signal at these sites. The missing data for the two stations were interpolated linearly by regression analysis. We calculated the regional monthly precipitation and temperature of the two stations for 1959–2002 to represent the regional climate records using the methods by *Jones and Hulme* [1996] (Figure 2). The regional mean annual temperature is about 1.8°C, and the mean yearly precipitation is 438.5 mm. The growing season in the study area is approximately May–September, with about 83% of the average annual precipitation received during the critical period of tree growth. In addition, relative humidity measured at the Zeku station during 1958–1990 was used in this study.

2.3. Sampling and Cross-Dating

[11] Tree cores were collected from Qinghai spruce (*Picea crassifolia*) in the Maixiu Forest Centre, located at 35°16′N, 101°57.44′E at an elevation of $\sim$3400 m (Figure 1). Annual growth in this tree species is sensitive to environmental change and has been widely used in palaeoclimate investigations in China [*Gou et al.*, 2005; *Liang et al.*, 2006a, 2006b; *Liu et al.*, 2007b].

[12] The trees sampled were growing on northwest-facing slopes with an inclination of 30–45°. A total of 47 increment cores from 27 trees were collected for cross-dating to establish the ring width chronology. The procedure of cross-dating has been described by *Wu et al.* [2006].

2.4. Isotopic Analysis

[13] According to the suggestion of *Leavitt and Long* [1984], pooling cores from four trees at a site for δ^{13}C analysis will yield an accurate absolute value. The methods of pooling the samples of the same year regardless of their mass/width and considering the respective ring width indicated the difference in average δ^{13}C was well in preparation and analytical error [*Leavitt et al.*, 1998; *Leavitt*, 2007]. Criteria for sample were low numbers of missing rings and regular ring boundaries. Six different trees without obvious damage signs were selected for isotope analysis. The rings were cut them into subsamples with 1-year resolution under a binocular microscope. For obtained reliable results, samples of different trees from the same year were pooled. The α-cellulose were extracted in order to avoid different isotopic signatures based purely on changes in the relative abundance of the individual constituents of the wood, each of which has a different isotope signature [*Loader et al.*, 2003]. We adapted the delignification procedure described by *Green* [1963] to facilitate batch processing of the samples [*Loader et al.*, 1997]. The cellulose was weighed and combusted to form CO_2 for stable carbon isotope analysis with an MAT-252 mass spectrometer (Finnigan MAT, Germany) in the State Key Laboratory of Cryospheric Science, Chinese Academy of Sciences [*Liu et al.*, 2007b]. The standard deviation of measurement during combustion and analysis was <0.1‰. The results were expressed as

Table 2. Correlation Matrix Between Climatic Records and Δ^{13}C Series (Pre, Precipitation; Tem, Temperature; RH, Relative Humidity; the Precipitation Has Been Transformed Logarithmically From the Previous July to the Current September Separately; Tem: October/p–December/p, Mean Temperature From the Previous October–December; Pre: June–July, Precipitation of June and July

Month	Tem	RH	Pre
Jul/p	−0.100	−0.071	0.164
Aug/p	0.013	−0.287	−0.146
Sep/p	0.054	0.147	0.264
Oct/p	**0.319**^{a}	0.237	**0.318**^{a}
Nov/p	0.208	−0.071	−0.071
Dec/p	0.235	−0.192	0.258
Jan	0.043	0.075	0.115
Feb	0.059	−0.005	0.220
Mar	−0.152	0.200	0.136
Apr	−0.216	0.233	0.140
May	−0.173	−0.072	−0.001
Jun	0.151	0.146	**0.556**^{b}
Jul	−0.221	0.049	0.266
Aug	−0.009	−0.326	−0.068
Sep	0.087	−0.096	0.153
Tem: Oct/p–Dec/p	**0.318**^{a}		
Pre: Jun–Jul			**0.487**^{b}

The humidity data are from Zeku station for 1959–1990. /p indicates the previous year.

[a] $P < 0.05$.

[b] $P < 0.01$.

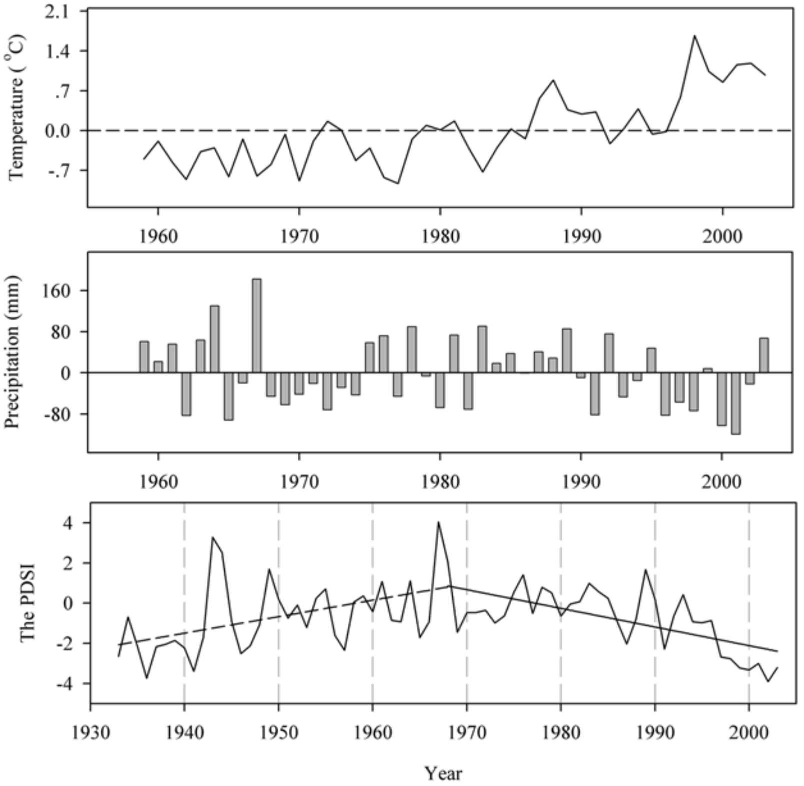

Figure 2. Departure of regional temperature and precipitation and variations of regional PDSI. Temperature (top): 1959–2003; precipitation (middle): 1959–2003; PDSI (bottom): 1933–2002.

δ-values relative to the Vienna Peedee Belemnite (V-PDB) standard:

$$\delta^{13}\mathrm{C} = \left\{\mathrm{R}_{(\mathrm{sample})}/\mathrm{R}_{(\mathrm{standard})} - 1\right\} \times 10^3 \text{per mil}, \quad \text{where } \mathrm{R} = {}^{13}\mathrm{C}/{}^{12}\mathrm{C} \tag{1}$$

2.5. Definitions and Basic Equations

[14] The carbon isotope discrimination (Δ^{13}C) in plant leaves associated with the carbon fixation by C_3 plants was expressed by *Farquhar et al.* [1989] as follows:

$$\Delta^{13}\mathrm{C} = \frac{\delta^{13}\mathrm{C}_{\mathrm{air}} - \delta^{13}\mathrm{C}_{\mathrm{plant}}}{1 - \dfrac{\delta^{13}\mathrm{C}_{\mathrm{plant}}}{1000}} \tag{2}$$

where Δ^{13}C is the carbon isotope discrimination by the plant. $\delta^{13}\mathrm{C}_{\mathrm{air}}$ and $\delta^{13}\mathrm{C}_{\mathrm{plant}}$ are the δ^{13}C values of ambient air and plant cellulose, respectively.

$$\Delta^{13}\mathrm{C} = a + (b - a) \times \frac{C_i}{C_a} \tag{3}$$

[15] The parameter a (=4.4‰) is the discrimination by diffusion of CO_2 from the atmosphere into the intercellular space of cells; b (=27.0‰) is the discrimination caused by isotope discrimination of RuBP carboxylase against $^{13}CO_2$; C_i and C_a are the concentration of CO_2 in the intercellular space of leaves, and in the atmosphere, respectively.

[16] Intrinsic water-use efficiency (iWUE) is defined as the ratio of the photosynthetic uptake of CO_2 through leaf stomata to the simultaneous transpiration loss of water vapor through the same opening [*Ehleringer and Cerling*, 1995], expressed in units of μmol $CO_2 \cdot \mathrm{mol}^{-1}$ H_2O:

$$\mathrm{iWUE} = \frac{A}{g} = C_a \times \frac{1 - \dfrac{C_i}{C_a}}{1.6} \tag{4}$$

where A is the rate of CO_2 assimilation by tree leaves, g is leaf stomata conductance, respectively.

2.6. Relationships Between Carbon Isotope Discrimination and Climate

[17] Relationships between carbon isotope discrimination (Δ^{13}C) and climate variables were identified by calculating Pearson's correlation coefficients [*Blasing et al.*, 1984]. Furthermore, dendroclimatic correlation and response functions [*Biondi and Waikul*, 2004] were calculated between monthly temperature, precipitation and Δ^{13}C. The bootstrap method [*Guiot*, 1991] was used for significance testing. As the PDSI index reached the early 1930s, we calculated the moving correlation functions (MCF) [*Biondi*, 1997; *Biondi and Waikul*, 2004] with the selected monthly PDSI index and Δ^{13}C series to investigate the temporal stability of climatic signals recorded in Δ^{13}C of tree rings using an 18-year moving window, which indicated the strongest interconnection between two indices.

3. Results

3.1. General Trends of Regional Climate and δ^{13}C Composition in Tree Rings

[18] As shown in Figure 2, the yearly mean temperature increased slowly during 1959–2003, especially during the

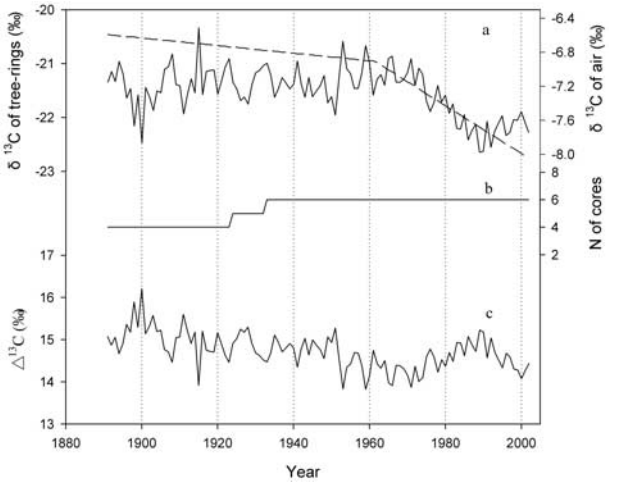

Figure 3. (a) The stable carbon isotope δ^{13}C series of tree rings. Dashed line indicates the trend of δ^{13}C in atmospheric CO_2 [*McCarroll and Loader*, 2004]; (b) sample depth; and (c) carbon isotope discrimination (Δ^{13}C) series.

late 1990s, and total precipitation showed a weak decreasing trend. In contrast to the warming trend during the last decade of the 20th century, precipitation was less than normal, resulting in more drought stress.

[19] The neighboring four PDSI series are significantly correlated ($P < 0.007$) during 1933–2003, suggesting a common climate-driven regional PDSI. Before the 1950s, the differences among the four series were somewhat greater (data not shown), resulting in a large standard deviation. The mean series of the nearest four PDSI grid data ranged from −4 to +4, with an upward trend before the mid-1960s, indicating increasingly wetter conditions, and a downward trend at the end of last century indicating increasingly drier conditions (Figure 2).

[20] The δ^{13}C series increased from 1890 to 1960, then decreased to 1990. It is noteworthy that during the last 10 years, the δ^{13}C series showed an increasing trend (Figure 3a), corresponding to severe drought. As a whole, the Δ^{13}C series exhibited three phases (Figure 3c). First, it showed a long-term downward trend from 1890 to the 1970s, and then increased to the 1990s, followed by a decrease to the end of the last century.

3.2. Carbon Isotope Discrimination-Climate Relationships

[21] The averaged climate records from the Tongren and Zeku meteorological stations include monthly temperature and precipitation covering the period 1959–2002, and relative humidity for the Zeku station for 1959–1990. The observed climate data were transformed logarithmically to render the precipitation data approximately normal, and to reduce the effect of low and high-precipitation extremes [*Liu et al.*, 2004].

[22] In general, the correlation coefficient between Δ^{13}C in tree rings and individual meteorological parameters is not very high (Table 2). Δ^{13}C of Qinghai spruce exhibits significant positive correlations with precipitation in the previous (September-) October and the current June (-July) (Table 2). We also noted that the correlation of the mean temperature from the previous October to December was positive for tree ring Δ^{13}C. However, temperature during the growth season has only a small effect on Δ^{13}C. No significant relative humidity-related parameter has been found, as expected on the basis of theoretical considerations ($r = -0.326$, $P = 0.062$ for current August of 1959–1990). The bootstrap correlation function showed that the Δ^{13}C was negatively correlated with May and positively previous October temperature. Precipitation of previous winter and current June and July and Δ^{13}C are positively correlated (Table 3a). In contrast, Δ^{13}C was negatively correlated with May temperature and positively correlated with June-July precipitation as identified by the response function. This points to summer drought as the main climatic signal (Table 3b). These results suggest that throughout the physiological year, precipitation is the major factors affecting stable carbon discrimination.

[23] On the basis of these findings, the response of high-frequency variations between Δ^{13}C in tree rings and the most highly correlated climate parameters (during periods when the two parameters were correlated) were examined. High frequency is defined as the first difference of the data set (value of 1 year minus values of the previous year) that allows to determine the rate of change and to remove of long-term trends without altering or removing the existing data [*Loader and Switsur*, 1995; *Saurer et al.*, 1995]. The comparison of high-frequency variations indicated that temperature had only a minor effect on Δ^{13}C, whereas the total precipitation in June + July had a higher degree of correlation with plant Δ^{13}C than that in June alone (Figure 4). In addition, a significant correlation ($r = 0.519$, $P = 0.003$) was found between high-frequency Δ^{13}C and relative humidity in September and October of the previous growth season

3.3. Relationship Between Δ^{13}C and Regional Drought

[24] Because of the complexity of climate influence on Δ^{13}C, we analyzed correlations with PDSI for the months that had significant effects on Δ^{13}C (i.e., June and July) during the current growth season over their common period 1933–2002. The stable carbon discrimination (Δ^{13}C) and PDSI of June and of June + July do not display a significant correlation ($P = 0.153$ and 0.131, respectively) during the period of 1933–2002 (Figure 5). However, during the period of 1960–2002, these relationships are correlated significantly ($r = 0.523$, $P < 0.0001$ and $r = 0.488$, $P <$

Table 3. (a) Bootstrap Correlation and (b) Response Function Coefficients Calculated for the Period 1961–2001 Between the Carbon Isotopic Discrimination and Temperature (Tem) and Precipitation (Pre)[a]

	Previous Growth Year			Current Growth Year								
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Sep	Oct
						(a)						
Tem	/	0.289	/	/	/	/	/	−0.305	/	/	/	/
Pre	0.279	/	0.291	0.318	0.371	/	/	/	0.582	0.287	/	/
						(b)						
Tem	/	/	/	/	/	/	/	−0.206	/	/	/	/
Pre	/	/	/	/	/	/	/	/	0.297	0.192	/	/

[a] Coefficients with $P < 0.05$ were just showed.

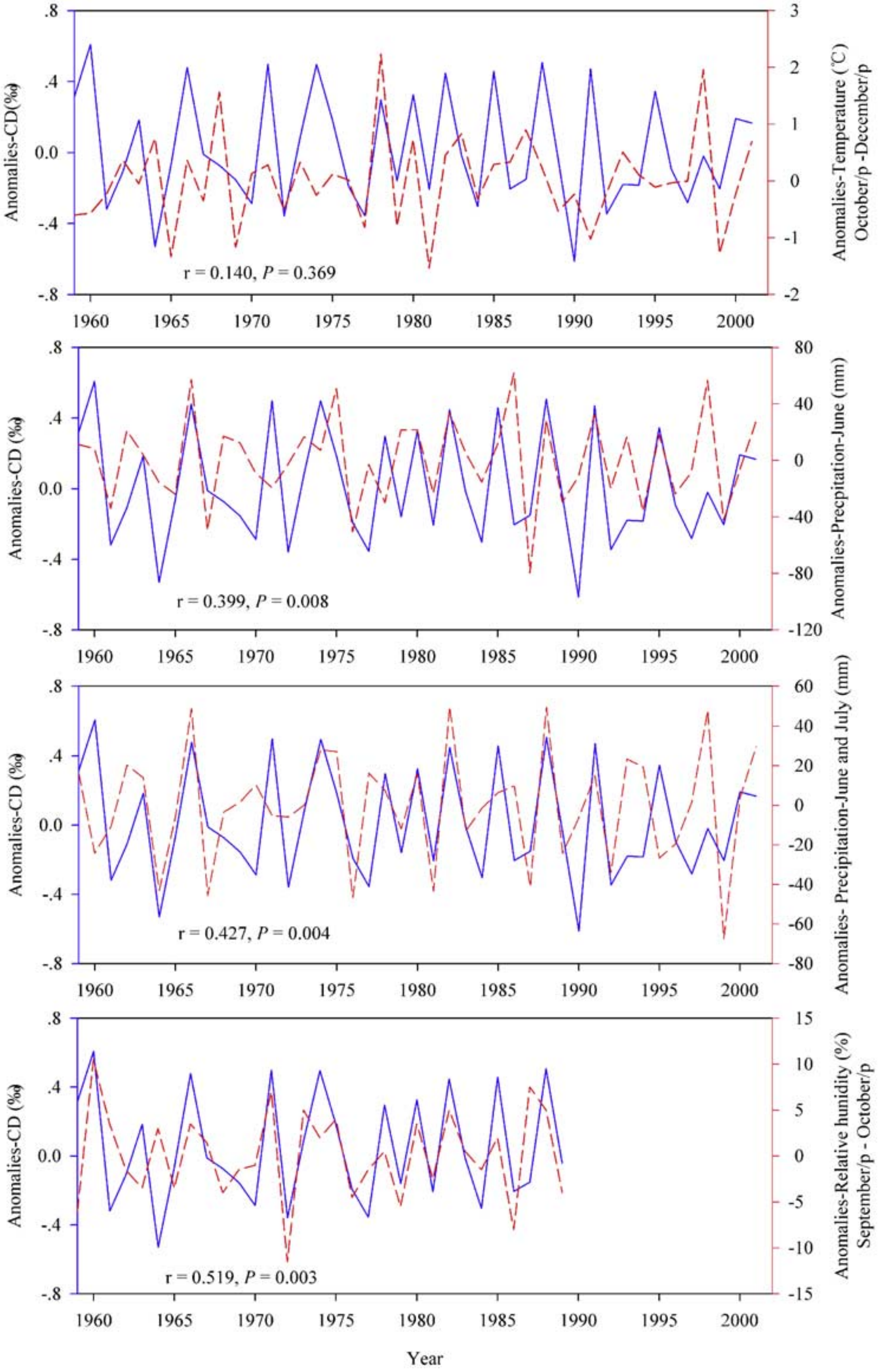

Figure 4. Correlations between high-frequency variations of carbon isotope discrimination (Anomalies-CD, blue line) and climatic variations (Red line) during 1960–2002. Anomalies-CD represents the first-order difference in carbon isotope discrimination; and Anomalies-Climatic parameters on the right-hand axis represent the first-order differences in climatic records. Solid lines indicate the variations of Anomalies-CD and dashed lines indicate the variations of each climatic parameter.

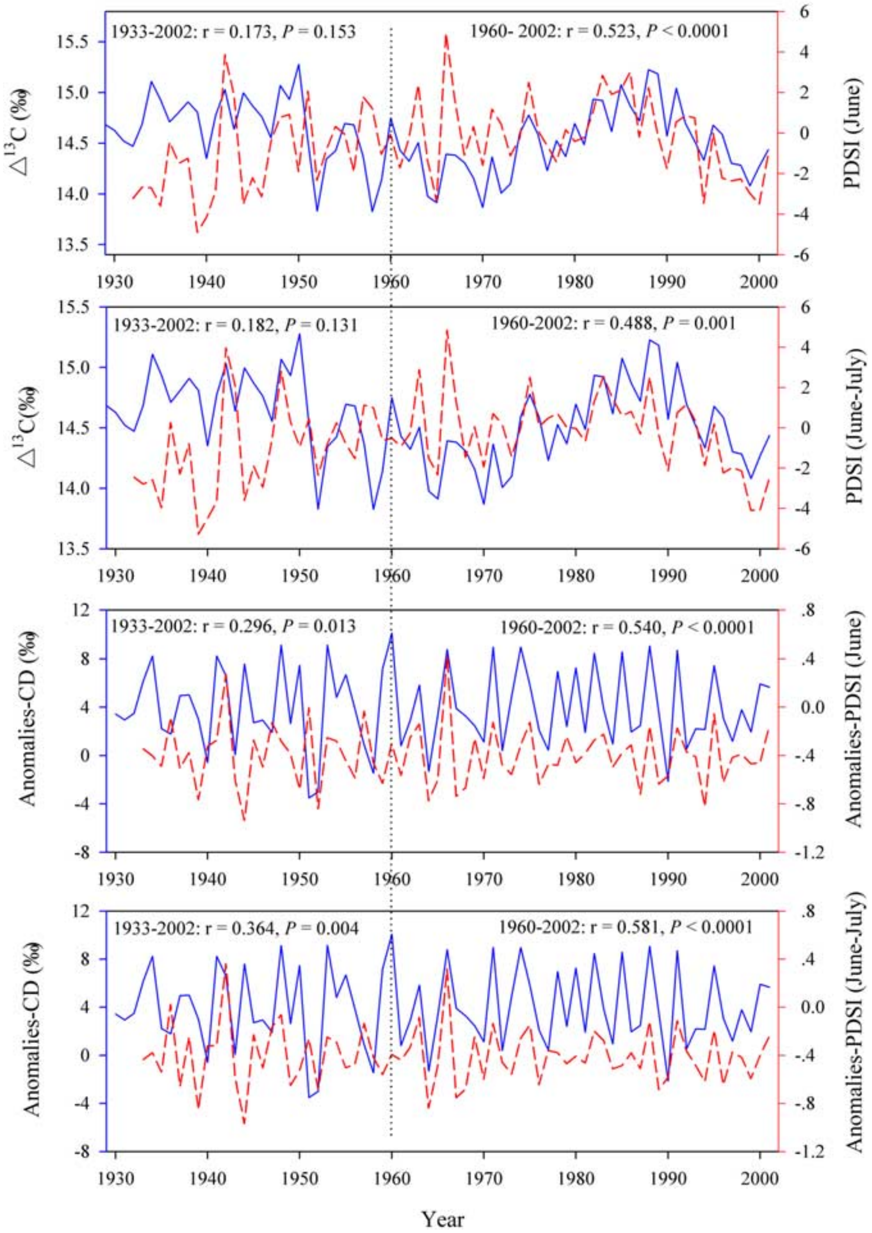

Figure 5. Time series of raw and first difference carbon isotope discrimination (Blue line) plotted separately with regional PDSI of June and the mean of June + July (Red line). Raw carbon isotope discrimination (Δ^{13}C) and High-frequency carbon isotope discrimination (Anomalies-CD) indicate the raw carbon discrimination and first-order difference of carbon discrimination. Anomalies-PDSI indicates the high-frequency variations (first-order differences) of the regional PDSI index. Solid lines indicate the variations of Δ^{13}C and Anomalies-CD, and dashed lines indicate the variations of the PDSI index of different months.

0.001). Before 1960, the correlation between Δ^{13}C and PDSI was weaker. The correlation coefficients for the high-frequency Δ^{13}C and PDSI of June or June + July improved relative to those of the raw data sets exceeding the confidence limit ($\alpha = 0.01$). This means that the correlation between Δ^{13}C in tree rings and regional PDSI is strongest for first differences (Figure 5), while long-term trends are influenced more strongly by other effects. During 1960–2002, the correlation coefficients between high-frequency variations of Δ^{13}C and PDSI of June and June + July are 0.540 ($P < 0.0001$) and 0.581 ($P < 0.0001$), respectively. Despite the loss of degrees of freedom resulting from short records, the high-frequency correlations between Δ^{13}C and PDSI are even more significant.

[25] Moving correlation function (MCF) analysis was carried out on Δ^{13}C and June and July PDSI index to investigate the temporal stability of the main climatic signals (Figure 6). MCF analysis indicates a progressive

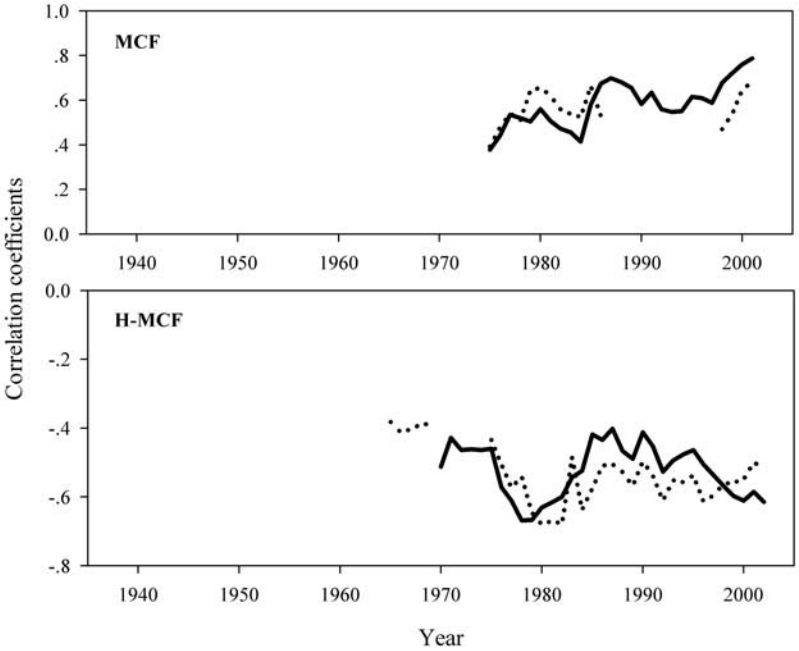

Figure 6. Moving correlation functions (MCF) calculated between PDSI index of selected months and carbon isotope discrimination. MCF and H-MCF show temporal variation of raw and high-frequency series of carbon isotopic discrimination and PDSI, respectively. Period: 1933–2001; moving windows: 18 years. The solid line (June) and dashed line (July) show periods of correlation coefficients with $P < 0.05$.

positive trend of the correlation of Δ^{13}C and PDSI of June–July covering the period of 1975–2001 (Figure 6, upper panel). For high-frequency variations, the negative correlations between anomalies-PDSI and anomalies-CD (H-MCF) appear to increase from 1965 to 2001 (Figure 6, lower panel). Both MCF analyses suggested that the relationship between carbon isotope discrimination of trees and drought stress became more intimate during the increasing regional temperature trend (Figure 6).

3.4. Variations of Intrinsic Water Use Efficiency

[26] A plot of iWUE and atmospheric CO_2 concentration (C_a) (Figure 7) shows that during 1890–1990, iWUE decreased with increasing atmospheric CO2, suggesting decreased sensitivities of iWUE at higher levels of atmospheric CO_2. However, during the last decade, this trend reversed, with a sharp increase of 7.69% compared to the average of the previous decade. This enhancement of iWUE is mainly caused by extreme drought stress. The difference between function *a* and function *b* (Figure 7) is mainly caused by extremely drought stress and should be considered in the exact evaluations of long-term iWUE variations in response to atmospheric CO_2 enrichment.

3.5. Climate Implications of δ^{13}C in Tree Rings for Climate Reconstruction

[27] We determined climate-isotope relationships that can be useful for future reconstruction of climate variables. We used multiple regression analysis in an attempt to better understand the combined influence of different climate variables on carbon isotope discrimination. This was done for first differences of total precipitation of June + July (ΔP), temperature of the previous October–December (ΔT), and relative humidity of the previous September + October (ΔRH).

[28] The regression confidence levels of relative humidity ($P < 0.003$) and precipitation ($P < 0.001$), but not temperature ($P = 0.953$), are significant, suggesting a minor effect of temperature and crucial effects of moisture on carbon discrimination. The effects on Δ^{13}C of relative humidity

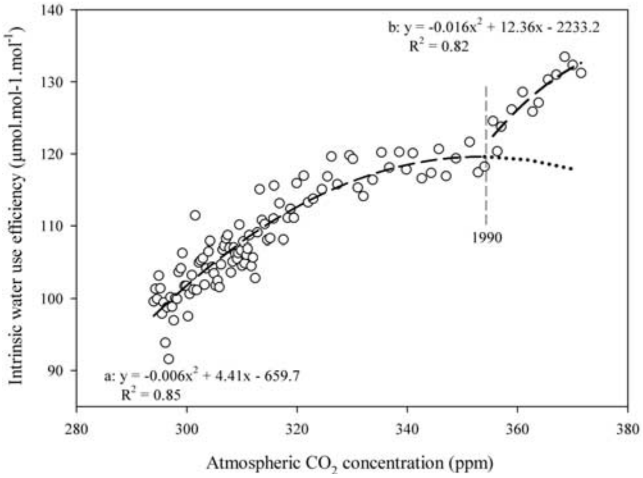

Figure 7. Annual values of intrinsic water-use efficiency (iWUE), plot against atmospheric CO_2 concentration. Second-order polynomial trend lines are shown. Functions *a* and *b* were the regression of the iWUE covering the periods of 1890–1900 and 1901–2002. The dashed line is the extrapolation of function *a*.

and precipitation are positive, and the effect of temperature is negative. The final regression function has the lowest Akaikie's Information Criteria (AIC).

$$\text{Anomalies} - \text{CD} = 0.043 + 0.003\ \Delta\text{RH} + 0.006\ \Delta\text{P}, \quad \text{R}^2 = 0.49, P < 0.0001$$

[29] In function, anomalies-CD represents the high-frequency variation of Δ^{13}C series. ΔRH and ΔP are the high-frequency variations of relative humidity and precipitation.

[30] We calculated two regression functions because of the differences between PDSI and carbon discrimination in the periods 1933–2002 and 1960–2002,

$$\text{For } 1933-2002: \ \text{H}-\text{CD} = 3.937\text{H}-\text{PDSI}_{\text{June-July}} - 0.137, \quad \text{R}^2 = 0.337, \quad P < 0.0001$$

$$\text{For } 1960-2002: \ \text{H}-\text{CD} = 4.138\text{H}-\text{PDSI}_{\text{June-July}} - 0.073, \quad \text{R}^2 = 0.369, \quad P < 0.0001$$

[31] H-CD and H-PDSI$_{6-7}$ represent the high-frequency variation of Δ^{13}C series and PDSI series of current June + July, respectively. These strong correlations between Δ^{13}C and drought indices derived from modern climate data suggest that carbon isotopes in tree cellulose are an effective proxy for reconstructing drought in this region of the Tibetan Plateau.

4. Discussion

4.1. Upward Shift of δ^{13}C During the Last Decade

[32] From 1960, a decrease in δ^{13}C is expected due to the burning of fossil fuels, corresponding to a decrease of δ^{13}C in atmospheric CO_2 [*McCarroll and Loader*, 2004]. However, there was an upward trend during the last decade in our δ^{13}C series. On the basis of observed climate data, during 1990–2002, the climate warmed continuously, but precipitation was less than normal, which changes the balance of available water reserves in the soil and water vapor of the atmosphere (Figure 2). *Zou et al.* [2005] found that drought areas increased significantly in Northwest China during 1951–2003. In addition, most of northern China (except western part of China) has experienced severe and prolonged dry periods since the late 1990s to the present [*Zou et al.*, 2005; *Ma and Fu*, 2006]. Therefore this interesting upward trend of δ^{13}C is a result of the dry conditions for plant growth, which can be explained by mechanisms that control the ^{13}C/^{12}C ratios in C_3 plants [*Francey and Farquhar*, 1982; *Farquhar et al.*, 1982].

4.2. Response of δ^{13}C to Climate

[33] Several possible global drivers could account for the observed trends in α-cellulose δ^{13}C in mature alpine forests, including changes in atmospheric CO_2 concentration, temperature, precipitation, relative humidity, and nutrient deposition (reviewed by *McCarroll and Loader* [2004]). During the arid year, water stress induces stomatal closure and lower stomatal conductance, reduces the ratio of intercellular to atmospheric CO_2 concentrations (C_i/C_a), and reduces discrimination against $^{13}CO_2$, thus increasing δ^{13}C and decreasing Δ^{13}C [*Farquhar et al.*, 1982]. The effects of temperature, precipitation and relative humidity on α-cellulose δ^{13}C are exhibited mainly as high-frequency fluctuations, whereas the long-term trend in δ^{13}C is controlled mostly by the δ^{13}C content of atmospheric CO_2. However, the long-term trend in Δ^{13}C is due to the increased iWUE in response to increasing CO_2 concentration in atmospheric CO_2 [*Feng*, 1998].

[34] As shown in Table 2, significant positive correlations exist between Δ^{13}C and precipitation in the previous October and June (a negative relationship between δ^{13}C and precipitation). Trees benefit from precipitation in the year before the growth ring is formed due to enhanced soil moisture storage. A higher precipitation in the current growth season is also of benefit to tree physiological activities [*Liu et al.*, 2004]. The higher temperature in May will result in more water loss, giving serious water stress on tree's physiological activities (Table 3b). More precipitation in current summer (June and July) is favorable to tree growth due to less water stress, which can be explained by the theory of carbon isotope discrimination [*Farquhar et al.*, 1982; *Ehleringer*, 1995; *Lin et al.*, 1996].

[35] The time series of high-frequency data shows that not all parameters display the same relationship. Low-frequency variations of Δ^{13}C are controlled both by temperature and water stress, but high-frequency variations mainly reflect water stress, indicating a minor effect of temperature. The Δ^{13}C values of these trees are correlated positively with changes in relative humidity and precipitation, indicating a dominant soil moisture control on the carbon response to these variations. The positive relationship between Δ^{13}C values and water stress controls verifies the high degree of stomatal limitation of photosynthesis [*Farquhar et al.*, 1982].

[36] Experimental results show that the photosynthetic capacities of tree seedlings are reduced during long-term elevated CO_2 treatment, resulting in slowing the rate of increase of iWUE [*Sheu and Chang*, 2001]. This response pattern of iWUE of trees to increasing CO_2 concentration was found in northern European tree ring studies [*Waterhouse et al.*, 2004], and this behavior has implications for regional estimations of future terrestrial carbon storage. In our study, the increase of iWUE during the last decade is mainly a result of drought stress. In addition, the effect of atmospheric CO_2 enrichment is imposed on this trend. Removal of drought stress effects on iWUE may benefit the assessment of long-term changes in water use efficiency in response to enrichment of atmospheric CO_2. Because the enrichment of atmospheric CO_2 concentration has significant effects on plant photosynthetic rate and soil organic carbon sink [*Gill et al.*, 2002], our results implied that water-stress due to drought may have had a detrimental effects on spruce's ability to assimilate carbon, further on forest and soil carbon budget.

4.3. Implications for Reconstruction of Drought Patterns

[37] Correlation between Δ^{13}C and climatic parameters indicated that moisture conditions are the limiting factors for Δ^{13}C (Tables 2 and 3 and Figure 4). This correlation is shown also by the analysis of PDSI and Δ^{13}C series (Figure 5). The PDSI for east part of Northwest China by *Ma and Fu* [2006] and *Dai et al.* [2004] showed similar

patterns of drought trends during 1960–2003, and four PDSI grid series from *Dai et al.* [2004] show consistent and significant trends. However, the high correlation among the four series decreases before 1960. The differences in relationships between PDSI and $\Delta^{13}C$ in different periods may be a result of the short instrumental climatic records. The PDSI data before 1960 contain more results estimated by interpolation, which can introduce greater uncertainties. Moreover, our study region was located in a mountainous area where the climatic conditions are variable and highly complex. The great heterogeneity of the local environment can contribute errors to estimated values of PDSI. From Figure 2, the PDSI of 1935–1942 and 1997–2003, are lower than -2, indicating moderate to severe drought stress. The $\Delta^{13}C$ values of these periods are not at the same levels, suggesting dissimilar drought response. A possible explanation is aging trends; although the first 10 years of every ring core were not used, the aging trends of $\delta^{13}C$ are not eliminated completely because the "juvenile effects" of trees may go on more than 10–30 years [*Freyer*, 1979; *Anderson et al.*, 1998]. Moreover, the long-term trends of $\Delta^{13}C$ also reflect the ecophysiological effects superimposed on the environmental trends [*Li et al.*, 2005]. On the basis of the results described above, we consider that $\delta^{13}C$ in tree rings has the potential for drought patterns reconstruction in a high-altitude region such as the Tibetan Plateau. Our results will therefore be useful to assess possible future changes in forest growth related to climate. However, more ecophysiological studies related to carbon isotope discrimination are needed, especially for evaluating the spatial and temporal variability of climate-forest interactions in the high mountains forests on the Tibetan Plateau.

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