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Combined view of various tree ring parameters from different forest habitats in Tibet for the reconstruction of seasonal aspects of Asian Monsoon variability

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ABSTRACT

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Tibetan forests cover a wide range of ecological habitats. Three different types of tree limit can be derived from statistical climate-growth relationships: An alpine timberline, where growth is limited by temperature conditions, a semiarid tree limit, where available moisture is the minimum factor for tree growth, and dry, southfacing exposures near the upper treeline, where growth can be limited as well by temperature as by moisture conditions. Trees at each of these sites, which belong to the genera *Pinus, Picea, Abies* and *Juniperus* are sensitive to specific seasonal climatic elements e.g., summer precipitation, summer or winter temperature. The potential for the selective reconstruction of different seasonal aspects of climate is enhanced by considering different tree ring parameters like total ring width (TRW), maximum latewood density (MLD), wood anatomy and the content of $\delta^{13}C$ in wood cellulose. The combination of these seasonal climate related parameters provides a more comprehensive view of climate variability over the year, allowing the reconstruction of synoptic weather conditions. These are much better indicators for wind system dynamics and monsoon variability than one single meteorological factor alone. Since juniper can reach living ages of more than 1300 years in Tibet, dendroclimatological studies offer the possibility to reconstruct monsoon variability on the Tibetan Plateau and adjacent regions during the last millennium.

Key-words—Monsoon, Tibet, Forest, Ring width, Climate.

एशियाई मानसून की परिवर्तनशीलता के मौसमी परिप्रेक्ष्य की पुनर्रचना हेतु तिब्बत के विभिन्न वन आवासीयों से प्राप्त विभिन्न वृक्ष वलय प्राचलों का एकीकृत विश्लेषण

अख़िम ब्राउनिंग

सारांश

तिब्बत के वनों में पारिस्थितिकीय आवासीयों की वैविध्यमयता विद्यमान है। वृक्ष सीमाओं के तीन भिन्न-भिन्न रूप सांख्यिकीय जलवायु-वृद्धि सहसम्बन्धन से प्राप्त किए गए हैं : एक अल्पाइन वृक्ष सीमा, जहाँ वृद्धि तापमान की स्थितियों में सीमित है; एक अर्द्धशुष्क वृक्ष सीमा, जहाँ उपलब्ध आर्द्रता वृक्ष वृद्धि हेतु न्यूनतम कारक है तथा ऊपरी वृक्ष सीमा के

समीप शुष्क उत्तराभिमुख अनावरण, जहाँ वृद्धि को तापमान एवं आर्द्रता की स्थितियों में सीमित किया जा सकता है। इनमें से प्रत्येक स्थलों पर वे वृक्ष, जो *पाइनस, पाइसिया, एबीज़* तथा *जूनीपेरस* वंश से सम्बन्धित हैं, कुछ विशिष्ट मौसमी जलवायुविक तत्वों, जैसे- ग्रीष्म वृद्धि, ग्रीष्म अथवा शीत तापमान के प्रति संवेदनशील हैं। जलवायु के विभिन्न मौसमी पहलुओं की चयनित पुनर्रचना हेतु आवश्यक आधार को विभिन्न वृक्ष वलय प्राचलों, जैसे- सकल वलयी चौड़ाई (टी.आर. डब्ल्यू.), अधिकतम पश्च काष्ठ घनत्व (एम.एल.डी.), काष्ठ शारीर विज्ञान तथा काष्ठ सेलुलोज में $\delta^{13}C$ के तत्व से बल मिलता है। इन मौसमी जलवायु सम्बन्धी प्राचलों का संयोजन साररूपी मौसमी स्थितियों की पुनर्रचना को प्रदर्शित करते हुए सम्पूर्ण वर्ष में जलवायु की विविधता का अपेक्षाकृत अधिक समग्र परिदृश्य प्रदान करता है। ये पवन तंत्र गतिविज्ञान तथा मानसून विविधता हेतु एकमात्र मौसमी कारक की अपेक्षा अधिक उत्कृष्ट संकेतक हैं। चूँकि जूनीपेर तिब्बत में 1300 वर्षों से अधिक जीवनकाल तक ही पहुँच सकता है, अतः वृक्षजलवायुविक अध्ययन से तिब्बत के पठार एवं समीपवर्ती क्षेत्रों में विगत सहस्राब्दि के दौरान मानसून परिवर्तनशीलता का पुनर्सृजन सम्भव है।

संकेत शब्द—मानसून, तिब्बत, वन, वलय चौड़ाई, जलवायु.

INTRODUCTION

USUALLY certain tree-ring parameters like maximum latewood density at subalpine sites or ring width under semiarid conditions, show high correlations with specific seasonal climate elements like summer temperature in the former or summer precipitation in the latter case. Therefore, the majority of dendroclimatic studies are limited in reconstructing one or a few seasonal aspects of climate at best.

The mountain regions of eastern Tibet show a variety of climatic conditions and hence a tremendous diversity of ecological forest types and tree habitats. This allows to combine several wood parameters which are sensitive to different seasonal climate elements. Thus, the reconstruction of climate over the whole course of a calender year may become possible. The identification of changing synoptic weather conditions helps to gain deeper insight into the variation of climate in southern Asia.

CHARACTERISTICS OF CLIMATIC CONDITIONS AND METEOROLOGICAL DATA

The subtropical high plateau of Tibet receives an immense amount of solar radiation in spring and summer and therefore acts as a huge heating surface, resulting in a strong low pressure cell over the plateau (Murakami, 1987). This causes moist air masses over the Indian Ocean and the Bay of Bengal to flow northward and bring moisture to southern and high Asia. As a result, 70 to 80% of the total annual precipitation in Tibet falls during the season of the Indian Summer Monsoon (ISM) between late June and middle of September. However, this general picture is strongly modified by mountain topography (Schweinfurth, 1981). Local diurnal circulation systems cause an ascent of unstable air masses, so that a great amount of summer precipitation is of convective character (Flohn, 1987). The Himalaya-Hengduan Shan mountain chains form a natural barrier for the monsoonal air masses to flow northward. The deeply incised gorges of the upstreams of Nu Jiang (Salween), Lancang Jiang (Mekong), Jinsha Jiang (Yangtze) and Yarlung Tsangpo (upstream of Brahmaputra), therefore act as pathways for the monsoon (Chang, 1981), resulting in a steep moisture gradient from south-east to north-west in Southern Tibet.

During winter, when dry and cold air masses that originate from central Asia prevail, the Tibetan Plateau acts as a heat sink and is colder than the surrounding free atmosphere. Western disturbances bring little precipitation in the form of snow. Apart from Mountain areas, the snow cover usually does not persist due to the immense insolation even in winter. However, the intensity of the Eurasian winter and the depth of the snow cover over Tibet and the Himalaya have a strong influence on the ISM of the following summer, as has long been recognized by British meteorologists (e.g., Walker, 1910). Since the albedo is enhanced over snow, thermal energy is consumed to melt the snow and moist the soil surfaces after snowmelt. Therefore, the heating of the plateau surface is delayed and weakened after severe winters in Eurasia (Barnett *et al.*, 1988, Vernekar *et al.*, 1995). As a consequence, the low pressure cell over Tibet as the driving force for the ISM is not as strong as after a mild winter. Statistically, ISM and Eurasian Snow Cover (ESC) are negatively correlated and reduced amounts of monsoonal precipitation can often be observed after cold winters (Barnett *et al.*, 1988; Khandekar, 1991; Yang & Xu, 1994). Due to the marginal position at the northwestern fringe of influence of the ISM and the seasonal change of two competing circulation systems, the Tibetan Plateau is expected to be very sensitive to variations in the activity of the summer or winter circulation pattern.

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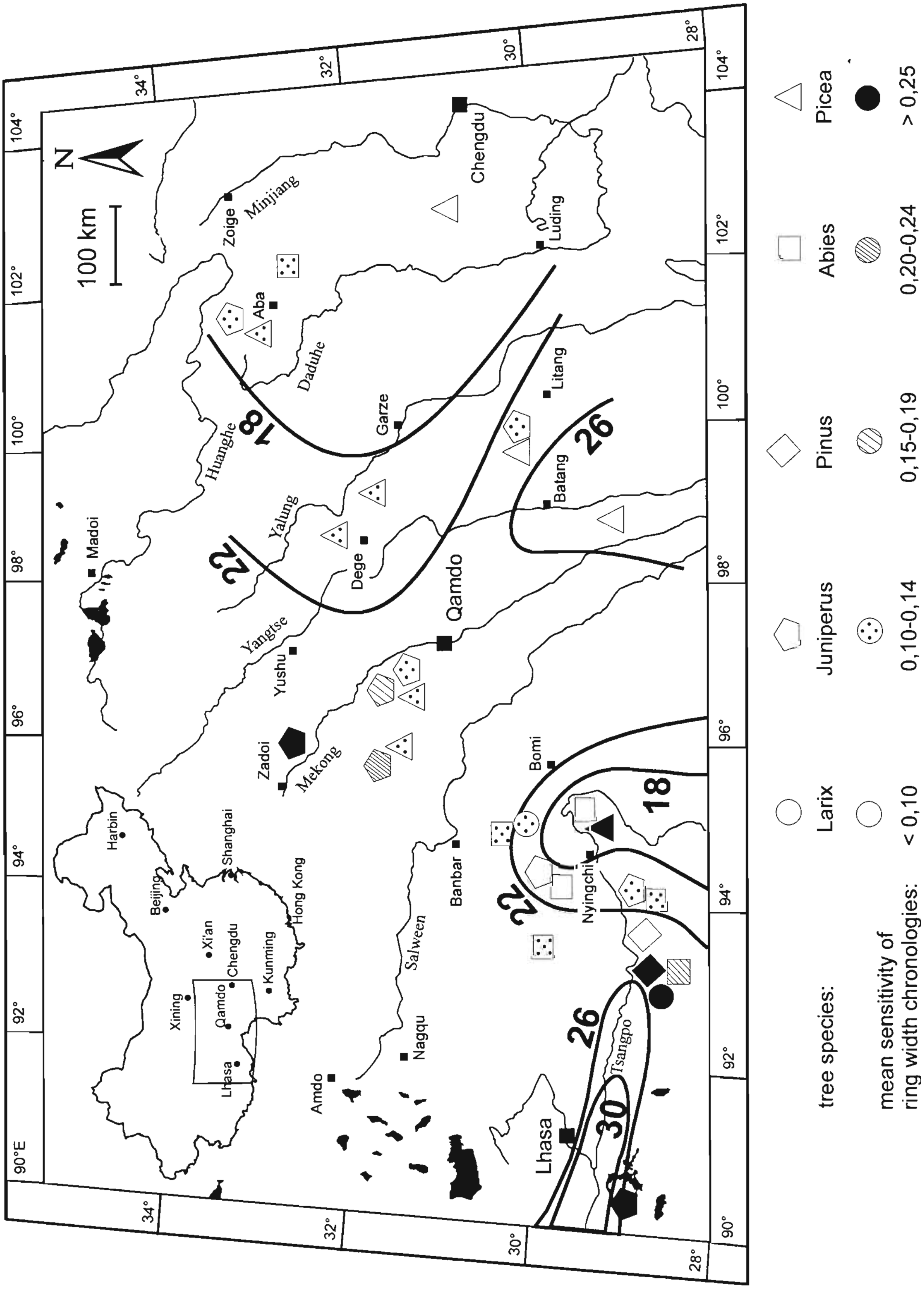
Fig. 1—Coefficient of variation of summer (June-September) precipitation and mean sensitivity (MS) of ring width chronologies.


N
100 km
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Hong Kong
Xi'an
Xining
Chengdu
Kunming
Qamdo
Lhasa
Madoi
Zoige
Minjiang
Aba
Daduhe
Huanghe
Garze
Litang
Luding
Yalung
Dege
Batang
Yangtse
Yushu
Zadoi
Mekong
Salween
Bomi
Banbar
Nyingchi
Nagqu
Amdo
Tsangpo
18
22
26
30
tree species:
Larix
Juniperus
Pinus
Abies
Picea
mean sensitivity of ring width chronologies:
< 0,10
0,10-0,14
0,15-0,19
0,20-0,24
> 0,25

Site name	Location	Elev. (m)	Tree species*	No. of trees	Time span/years
Wolong	30°53'N/ 102°50'E	3700	*Picea purpurea*	7	1842-1994 (153)
Zhegu	31°34'N/ 102°51'E	3950	*Abies fabri*	13	1737-1994 (258)
Zoige	34°02'N/ 102°43'E	3600	*A.* cf. *fargesii*	10	1830-1988 (159)
Gonggaling	33°00'N/ 103°42'E	3400	*A.* sp.	10	1679-1989 (311)
Aba	32°42'N/ 102°12'E	3850	*A.* sp.	23	1699-1991 (293)
Nianbaoyeze	33°13'N/ 101°16'E	4000	*Picea purpurea*	6	1728-1991 (264)
		4100	*Juniperus* sp.	7	1471-1991 (521)
Lhamcoka	31°49'N/ 99°05,5'E	4350	*Picea balfouriana*	20	1630-1994 (365)
Zagqen	32°07'N/ 98°51'E	4150	*P. balfouriana*	10	1699-1991 (323)
Haize Shan	30°18'N/ 99°30'E	4350	*P. balfouriana*	15	1777-1993 (217)
Haize Shan	30°18'N/ 99°29'E	4400	*Juniperus tibetica*	11	1174-1993 (820)
Gartog	29°40'N/ 98°31'E	4300	*Picea balfouriana*	14	1709-1993 (285)
Qamdo	31°05'N/ 96°57,5'E	4500	*P. balfouriana*	15	1406-1994 (589)
Qamdo	31°05'N/ 96°57,8'E	4600	*Juniperus tibetica*	14	1226-1994 (733)
Qamdo	31°07'N/ 97°02'E	4350	*J. tibetica*	34	449-1994 (1546)
Riwoqe	31°18'N/ 96°29'E	4300	*Picea balfouriana*	28	1673-1994 (322)
Riwoqe	31°17.5'N/ 96°30'E	4400	*Juniperus tibetica*	11	1354-1994 (641)
Zadoi	32°06'N/ 98°51'E	4300	*J. tibetica*	5	1445-1991 (547)
Nam	29°35'N/ 95°10'E	4100	*Abies* cf. *delavayi* var. *motouensis*	28	1740-1989 (250)
Nam		3350	*Picea* sp.	11	1846-1989 (143)
Gyalaperi	29°53'N/ 94°53'E	4000	*Abies delavayi* var. *motouensis*	12	1774-1993 (220)
Gyalaperi	29°54'N/ 94°53'E	3820	*Larix griffithiana*	20	1782-1994 (213)
Nyingchi	29°35'N/ 94°46'E	4300	*Abies delavayi* var. *motouensis*	27	1654-1993 (340)
Nyingchi	29°37'N/ 94°40'E	4300	*Juniperus* sp.	12	1568-1993 (426)
Chi	29°59'N/ 93°59'E	3900	*Abies delavayi* var. *motouensis*	10	1741-1994 (254)
Mainling	29°02'N/ 93°54'E	3430	*Pinus densata*	15	1765-1993 (229)
Mainling	29°04'N/ 93°57'E	4200	*Juniperus tibetica*	10	1047-1993 (947)
Mainling	29°03'N/ 93°57'E	4100	*Abies delavayi* var. *motouensis*	9	1664-1993 (330)
Langhsien	28°59'N/ 93°13'E	3500	*Pinus densata*	12	1760-1993 (234)
Langhsien	28°55'N/ 93°14'E	3700	*Abies* cf. *squamata*	13	1707-1993 (287)
			Larix griffithiana	8	1736-1993 (258)
Nakarze	28°58'N/ 90°28'E	4500	*Juniperus tibetica*	11(8)	1680-1994 (315)

Fig. 2—Tree-ring localities in Tibet referred to in this study.

The meteorological data that are available from the Tibetan Plateau do not extend further back than 1951, and in many cases the period of observations is less than 30 years. The meteorological stations are located near larger settlements in valley floors and are therefore not representative with respect to moisture conditions of most of the tree-ring sites investigated, which lie in a vertical distance of up to 1400 m. Like in other mountain areas, the spatial representativity of the precipitation data is not high and ranges from about 200 to 250 km, whereas temperature data show a correlation coefficient of more than 0.7 within 350 to 500 km (Boehner, 1996). As Vaganov *et al.* (1999) have shown, correlation between maximum latewood density (MLD) and temperature data could be improved from 0·52 to 0·67,by choosing pentads in relation to the beginning of the vegetation period, which can vary within 30 days, instead of monthly means of calendar-related periods. Unfortunately, data for the beginning of the vegetation period in different altitudinal belts are still lacking for Tibet. Moreover, lacking information about the effectiveness of rainfall events and short drought periods, that are not recorded in the monthly means of precipitation data, are further obstacles for a proper calibration between tree growth and climate.

RESULTS

Ecological diversity of tree limits in Tibet

It is known from many dendroclimatic studies that trees from dry forest habitats show a higher growth variability than trees from temperature limited sites. Fig. 1 shows the coefficient of variation for summer precipitation and mean sensitivity of ring width chronologies developed in Tibet. Details about the tree locations examined are given in Fig. 2 in the appendix. There is a general agreement between the precipitation gradient from east to west in northeastern and southern Tibet and increasing sensitivity of the trees. Fig. 3 shows a schematic transect through a mountain range west of Qamdo, indicating that this agreement is not spatially robust. Northern slopes are covered by dense forests of *Picea balfouriana*, and the upper tree limit lies around 4500 m.a.s.l. Southern exposures carry open forests of *Juniperus tibetica* which extends up to more than 4600 m. Below 4400 m, or other than south-facing slopes, the two species form mixed stands. The bottom of Lancang Jiang (Mekong) valley runs at 3200 m, but the lower parts of the slopes are presently devoid of forest. This might be a consequence of human activity, since there are remnants of settlements near Qamdo since neolithic times (Huang, 1994). The meteorological station at Qamdo registers an average annual precipitation of 474 mm which should be high enough to allow tree growth. Therefore, a site of *Pinus densata* from the Tsangpo Valley further to the west, that is supposed to grow under similar conditions, is shown on the left half of Fig. 3. The cut on the slope line and the question mark in the valley symbolize that it is only an assumption, that steppe forests of this type could have been existent near Qamdo as well.

Above the topographic cross-section, correlation functions between tree growth (TRW in case of *Juniperus* and *Pinus*, MLD in case of *Picea*) and the nearest meteorological station are shown (Qamdo in case of *Juniperus* and *Picea*, Tsetang in case of *Pinus*). It can clearly be seen, that MLD of spruce on northern aspects is clearly determined by temperature in August and September, whereas ring width (TRW) of pine shows high positive correlations with precipitation of July of the growth period, and summer precipitation of the year prior to growth, when the carbon storage for the formation of earlywood is assimilated. Correlations with temperature are negative during these months. In contrast to these two sites of very clear climate-growth relationships, there is no such clear dominance of one single climate element on growth at the juniper site. There are positive correlations with spring precipitation and summer temperature (and vice versa), so it can be assumed that dry and warm springs before the monsoon period cause drought stress at this site, while moist and cool summers lead to reduced growth rates at this high elevation. It may therefore be concluded that the growth of juniper for this region is in general controlled by temperature, but is far more sensitive to short-term or episodic drought periods than spruce on the neighbouring northern slopes.

As a consequence, three different types of ecological timberlines can be identified in Tibet, as indicated at the top of Fig. 3: a cold-moist tree-limit, where growth is exclusively limited by temperature conditions, a warm-dry tree-limit, where growth is usually controlled by the available amount of moisture, and a cold-dry tree-limit, where growth is mainly controlled by temperature, but where in dry years the influence of precipitation deficit prevails (Bräuning, 2000). These different ecological forest types can be used for the reconstruction of different climate elements, as it has already been demonstrated by LaMarche (1974) for *Pinus longaeva* in the White Mountains of California.

To support these findings, values of mean sensitivity (MS) which have been averaged for several chronologies of the particular type of tree-limit (number given in brackets in Fig. 3) show the highest sensitivity at the dry valley sites (0·34), the lowest values at the cold-moist sites (0·11) and intermediate values at the cold-dry sites (0·16). Therefore, the inconsistencies between MS and precipitation gradient in Fig. 1 can be explained by the ecological diversification of forest types due to topographic conditions and point to the importance of a proper ecological characterization of the forest types which are investigated.

Reconstruction of Seasonal Climate Elements

In the following paragraphs, the potential of various tree-ring features for the reconstruction of climate is discussed while particular emphasis is laid on the seasonal aspects of the climatic response of the different wood parameters.

Wood anatomical features

As it was shown by Bräuning (1999b), *Pinus densata* shows unusual wood anatomical features near its western limit of distribution, where the amount of available moisture is the growth-limiting climatic factor: in certain years, the majority of trees at this site forms density fluctuations which appear as bands of latewood-like cells within the earlywood (Fig. 4a). It could be shown that these density fluctuations mainly occur in years with deficit precipitation accompanied by warmer temperature in May and June (Fig. 4b). This is indicative of a delayed onset of the summer monsoon in southern Tibet in the corresponding years, causing above-average precipitation in July of the same years (Fig. 4b).In addition to the absolute amount of summer precipitation, that can be reconstructed from the high correlation between TRW

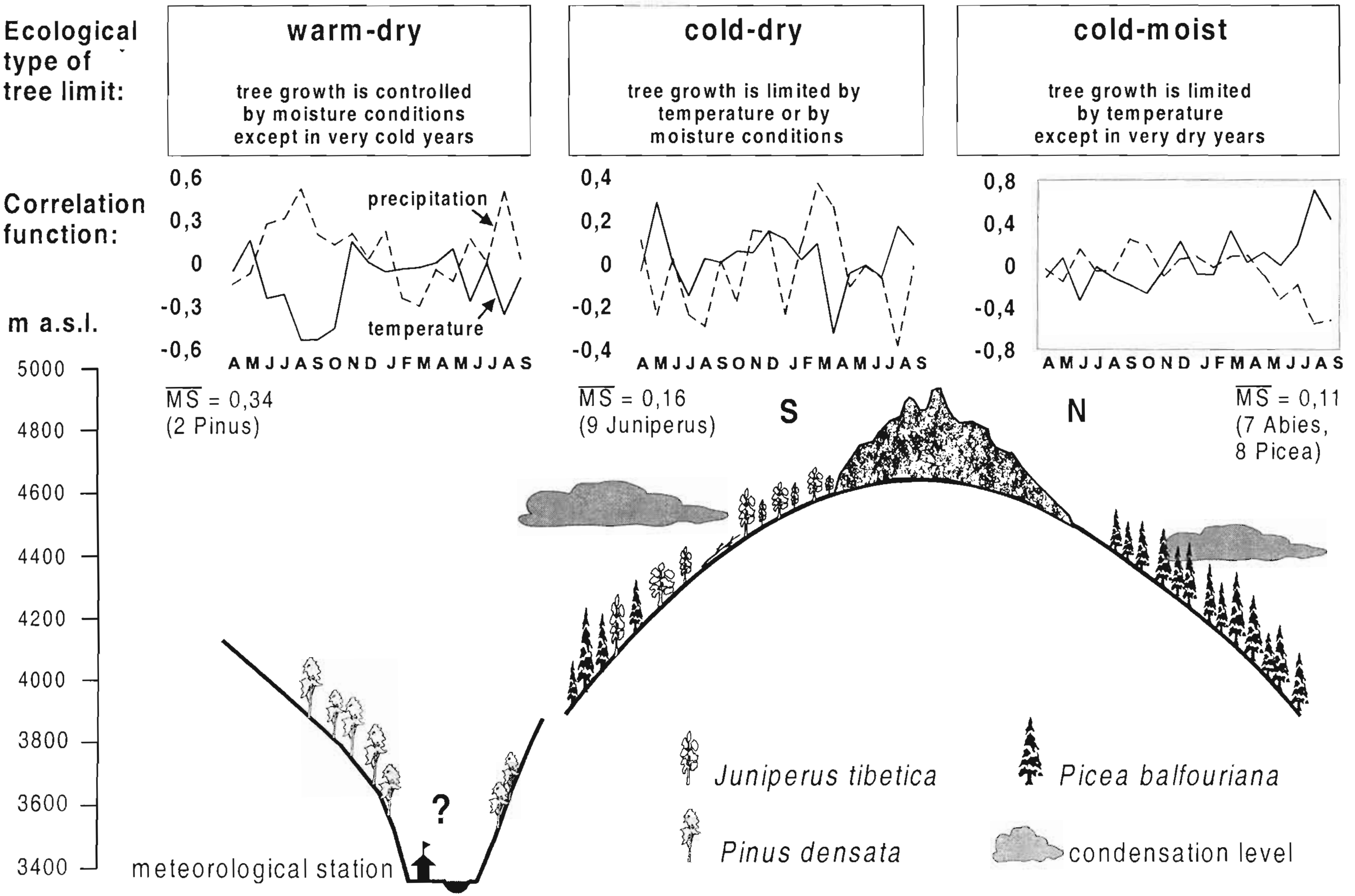

Fig. 3—Idealized profile of ecological forest types through a topographic section in eastern Tibet (Qamdo area, compare Fig. 1). In the upper section correlation functions between tree growth and meteorological data and derived ecological types of tree-limits are shown.

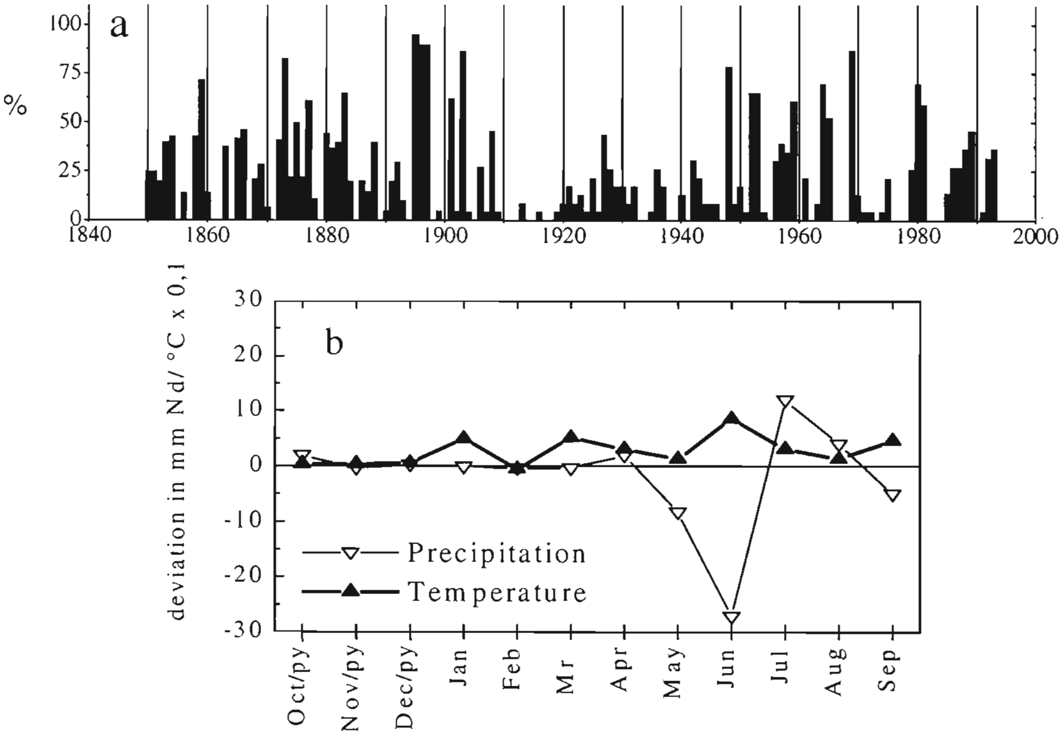

Fig. 4 — *a.* Frequency of density fluctuations (bands of latewood-like cells withing the earlywood) in growth rings of *Pinus densata* from the Tsangpo Valley *b.* Climatological situation at Tsetang (29°15'N, 91°46'E, 3553 m) in years of formation of density fluctuations (mean of the years 1958, 1959, 1964, 1969, 1985-1989, 1992), expressed as averaged deviations of monthly values of temperature and precipitation from October of the previous year (Oct/py.) to September (Sep). From Braeuning 1999b, changed.

and precipitation during summer and late summer in the prior vegetation period (Fig. 3), density fluctuations in trees of drought sensitive forest ecosystems provide information about the activity of the monsoonal circulation system.

Stable Carbon Isotopes

Under drought stress conditions, leaf stomata are closed and the heavy stable carbon isotope ^{13}C is increasingly incorporated into photosynthesis products. Thus, the isotope ratio ^{12}C/^{13}C in growth rings can be used as a proxy of climate conditions (Schleser *et al.*, 1999). The ^{13}C content in wood of *Juniperus tibetica* northwest of Qamdo has been measured for the last 1500 years (Zimmermann, 1998; Zimmermann *et al.*, 1997). In general, the isotope ratio follows the long-term trend of ring width at this site and seems to be determined by summer temperature. However, calibration efforts with recent meteorological data are not yet completed, so the results of this study shall be dealt with in detail in another paper.

Maximum Latewood Density (MLD)

In many mountain regions of the temperate zones MLD has proved to be closely linked with summer temperatures (Vaganov *et al.*, 1999; Luckman *et al.*, 1997; Schweingruber & Briffa, 1996). In Fig. 5, a regional master chronology of *Picea balfouriana* from central eastern Tibet is compared to summer temperature (August and September) of a composed meteorological series from the stations Derge and Qamdo (Fig. 1).

Unfortunately, this series covers only 32 years (1953-1984), so there is insufficient data for statistical verification of the results. The high linear correlation (r = 0·74) explains 55% of the variance of the MLD-chronology and can be used in a simple linear regression to reconstruct summer temperatures in eastern Tibet for the last 400 years (Fig. 5, Bräuning, 1999a, 2000).

Total Ring Width (TRW)

Under extreme site conditions, growth rates are mainly determined by one single climatological factor only. Near the dry distribution limit, growth of the specific tree species is controlled by moisture condition. As the exmaple of the stand of *Pinus densata* near Langhsien demonstrates, ring width chronologies from such sites show high correlations to summer precipitation and can be used to reconstruct summer precipitation (Bräuning, 1999a).

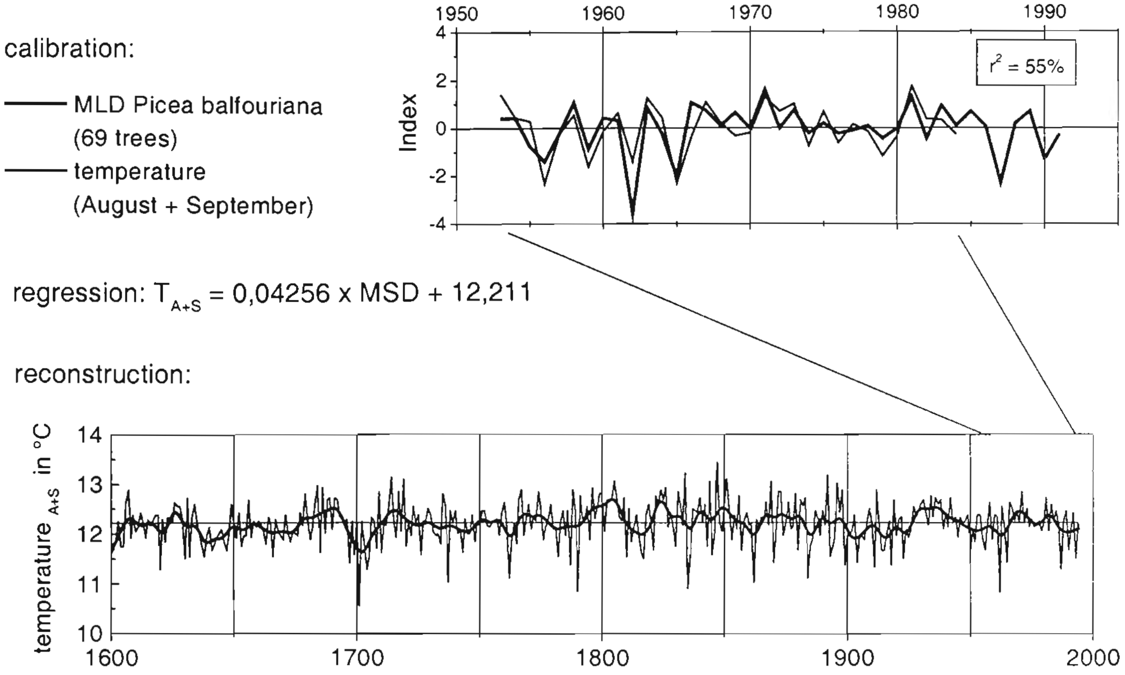

Fig. 5—Comparison between maximum latewood density (MLD) of *Picea balfouriana* and meteorological data and a reconstruction of summer temperature for the last 400 years for central eastern Tibet. Heavy line in the lower graph is the 5-year low-pass filtered series.

In contrast, ring width chronologies from *Picea* or *Abies* species from the upper timberline are sensitive to winter temperatures. The regional master chronology of *Picea balfouriana* from central eastern Tibet shows a correlation coefficient of 0·53 with temperature from November to December prior to the vegetation period (Fig. 6a) which is significant at the 99% confidence level. Cold winter temperatures might cause direct frost damage of the needles or may increase the risk of frost dryness, since solar radiation in subtropical mountain regions is considerable even during winter times. In addition, after cold winters with delayed snow melt, the following vegetation period is shortened, an early start of winter enhances the consumption of stored carbohydrates (Frenzel & Maisch, 1981), which may lead to a reduced earlywood width in the following year.

Many ring width chronologies are developed from tree stands which are not located near the tree limit of one of the two ecological types discussed above. They originate from sites with moderate conditions or from cold-arid timberlines (Fig. 3), where temperature as well as moisture conditions can limit growth in certain years. In such cases, there is no simple linear climate-growth relationship, and correlation coefficients between ring width and monthly climate elements decrease. The use of multiple regression techniques and the development of response functions (Fritts, 1976) can establish statistical relationships between ring width series and meteorological data which are in some cases able to explain more than 75% of the variance of the time series (Wu, 1992; Wu & Shao, 1995). In some cases, however, when a huge number of climatic variables are included into the regression equation, the results are difficult to explain from an ecological point of view.

Two alternative approaches can be applied to gain climatological information from such sites: The first is not to correlate ring width and single monthly meteorological series, but to use more complex climatic series which already integrate seasonal aspects of climate themselves. In Fig. 6b, a regional master chronology from eastern Tibet of *Juniperus tibetica* is compared with the Indian Summer Monsoon Index (ISM) which represents an area-weighted mean of precipitation from June to September over India and the area of snow cover over Eurasia in the preceeding winter (ESC) which has been derived from satellite images (Hahn & Shukla, 1976; Dey & Bhanu Kumar, 1983; Khandekar, 1991). ISM and ESC are negatively correlated (r = -0·55), but in Fig. 6b, the latter has been plotted in a reversed scale for a better visual comparison. The correlation coefficients between ring width index and ISM and ESC are 0·8 and -0·68 respectively and are significant on the 99·9% level. Since these trees represent cold-arid timberline sites (Fig. 3), the results show that warm and moist summers favour growth while cold and dry conditions lead to reduced ring width. In other words, growth rates from subalpine juniper sites can be used as indicators of whether the circulation system of the Indian Summer Monsoon or of the central Asian

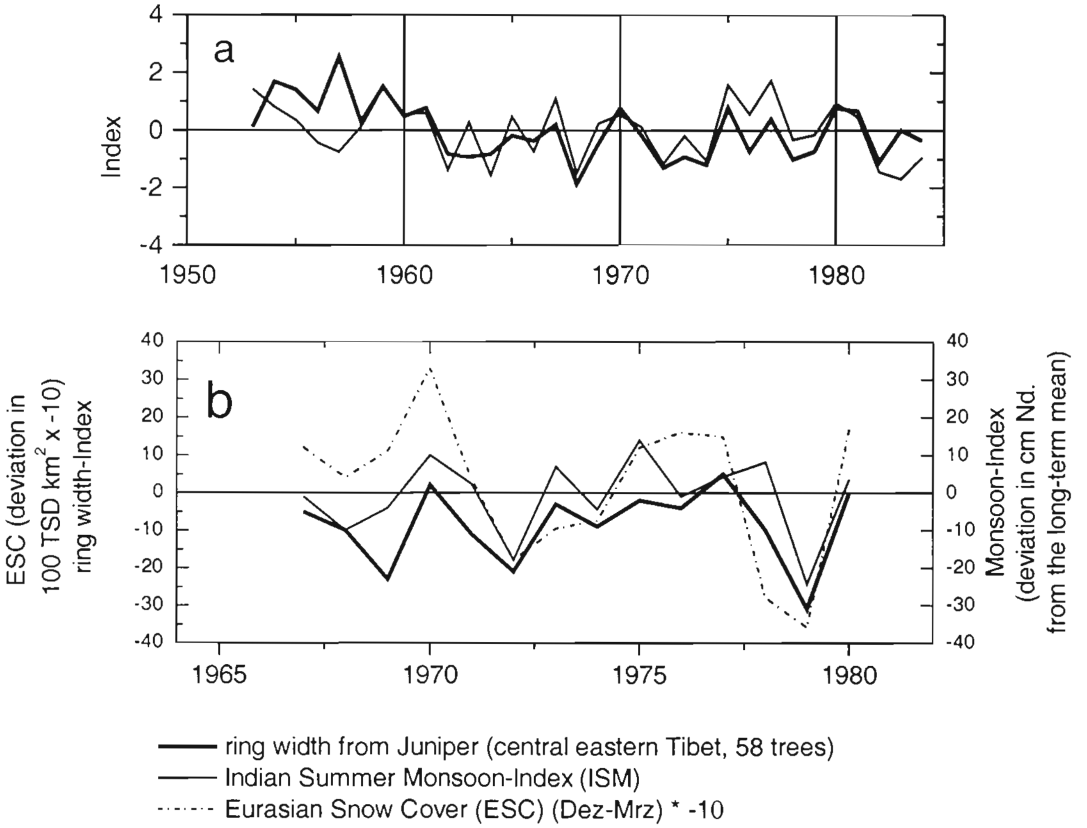

Fig. 6—*a*. Comparison between ring width of a regional master chronology of *Picea balfouriana* for central eastern Tibet and winter temperature. *b*. Correlation between ring width of *Juniperus tibetica* and indices of Indian Summer Monsoon (ISM) and Eurasion Snow Cover (ESC).

Winter Monsoon was more active. This is of special interest, since *Juniperus tibetica* can reach to the ages of more than 1300 years in Tibet (Bräuning, 1994, 1999a) and can thus provide information about the monsoon activity during different climate periods like the Little Ice Age or the medieval climatic optimum. However, it must be mentioned that if the longest existing ISM record of 124 years (1871-1994, Pant & Rupa Kumar, 1997) is compared with the juniper chronology, the correlation coefficient decreases below the 90% significance level. Although it is a well known fact that the relationship between tree-ring parameters and climate is not necessarily stable within periods of changing climate, this point needs further investigation.

This phenomenon is addressed by the second approach that can be applied for the climatological interpretation of ring width series, pointer year analyses. This approach tries to evaluate the climatological response of selected years in which the influence of climate on tree growth is particularly evident. In this study, such years were selected by the criterion of corresponding growth trends among the trees which are included in a local chronology: more than 75% of all trees must show the same growth tendency or interval trend (see Schweingruber *et al.*, 1990; Kaennel & Schweingruber, 1995 for terminology). The strength of the growth signal was calculated as the first difference of the ring width index chronologies from which the natural age trend of the trees was removed by a 50-years Kernal filter (Rinn, 1996), and classified as pointer value 1, 2 or 3 for being below or exceeding the first or second standard deviation, respectively.

In Fig. 7, the spatial pattern of ring width response under different climatological conditions is illustrated for three years (1966, 1968 and 1972). In 1966 (Fig. 7a), southern Tibet received between 28 and 80 mm excess precipitation in June. As a consequence, the dry forest sites in the Tsangpo Valley react with positive pointer intervals with values of 2 and 3, whereas subalpine sites in this area did not profit from the additional moisture. In contrast, 1968 (Fig. 7b) was a very cold year: annual mean temperature was below the long-term mean for about 0·8°C in eastern Tibet and for more than 1·2°C in western Tibet, respectively. Since this temperature depression affected the whole investigation area, the reaction of tree stands is uniformly negative. The most complex pattern is shown in Fig. 7c: In 1972, a bench of below-average precipitation in June stretches from the area south of Lhasa via Qamdo to the northeastern margin of the Tibetan Plateau. Within this area, dry sites in the Tsangpo Valley show reduced

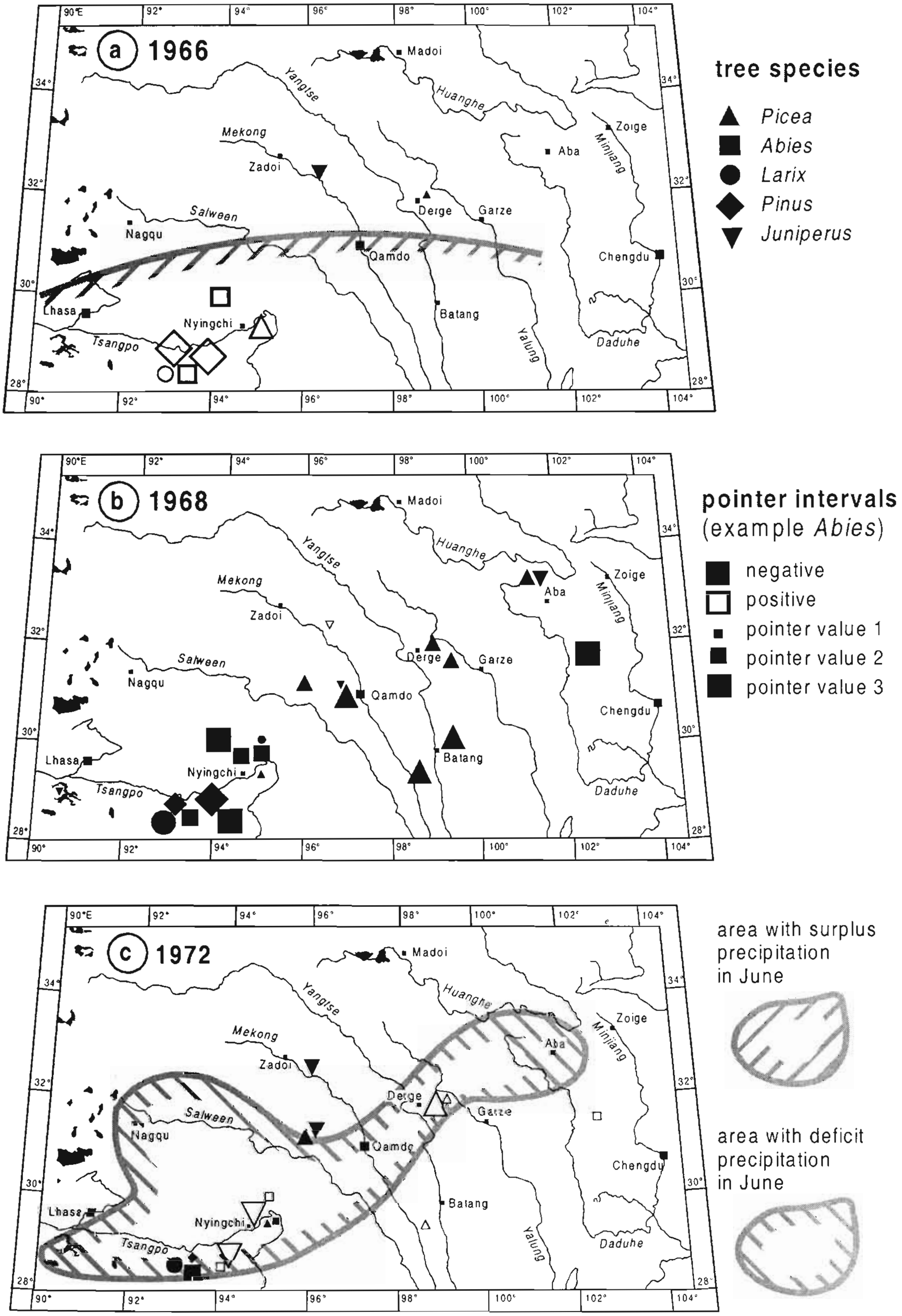

Fig. 7.—Pointer intervals of ring width series and their climatological interpretation.
a. surplus of early summer (June) precipitation in southern Tibet (1966)
b the whole year is cooler than the long-term mean (1968)
c. deficit of early summer (June) precipitation in southern and eastern Tibet (1972)

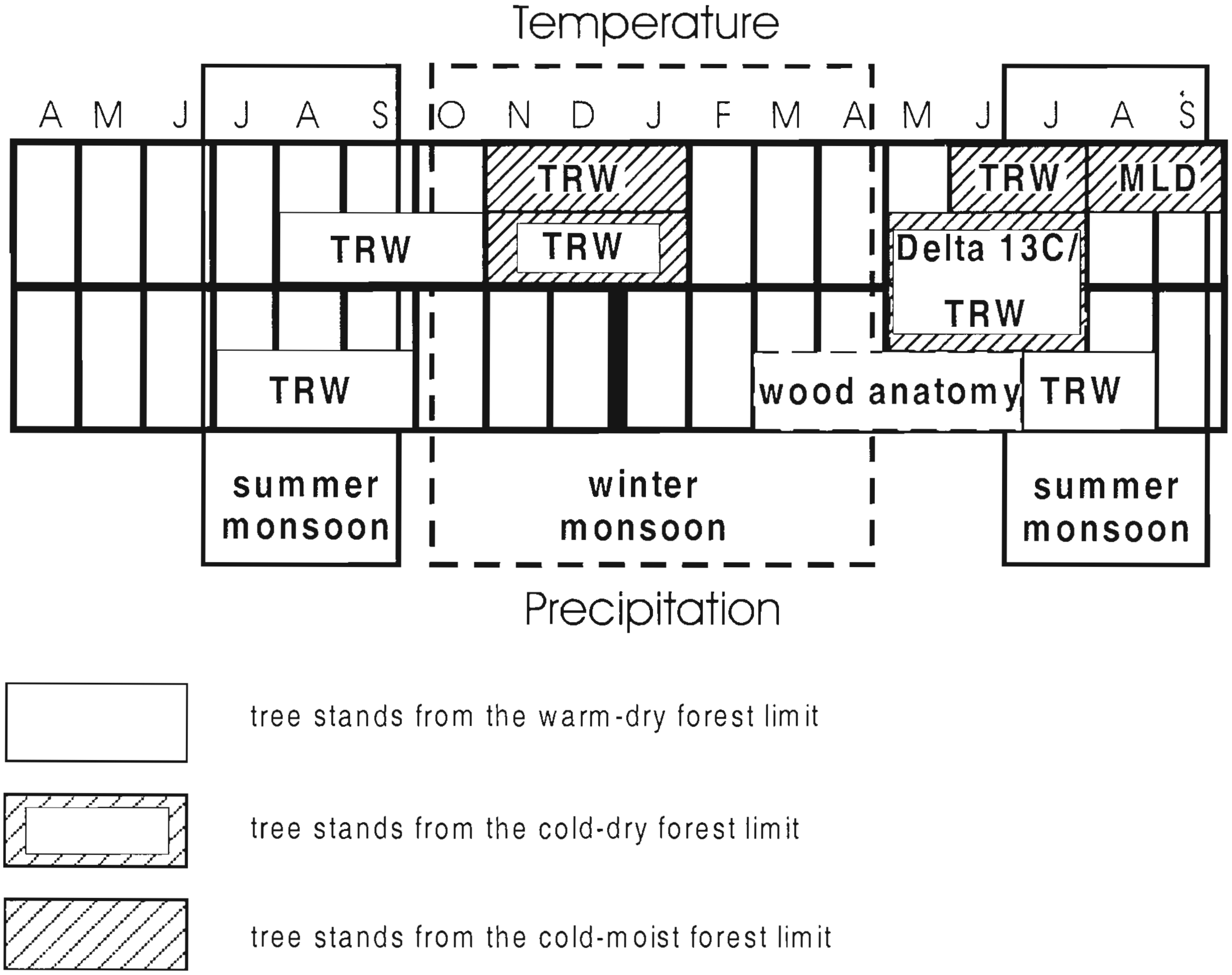

Fig. 8—Contribution of different tree-ring parameters to the reconstruction of seasonal aspects of monsoon variability. TRW = total ring width, MLD = maximum latewood density.

growth rates, whereas subalpine sites near Nyingchi and Derge profit from the drier and warmer conditions during early summer. In conclusion, the geographical pattern of growth reactions can be interpreted in terms of the underlying climatological conditions when forest types with different, well known ecological conditions are part of a sampling network (see Fig. 3 for comparison).

SUMMARY AND CONCLUSIONS

As shown above, several tree-ring parameters like ring width under different site conditions, MLD or wood anatomy can be used to reconstruct seasonal aspects of climate variability, as summarized in Fig. 8. Ring width series from the warm-dry forest limit can be used to reconstruct moisture conditions since they show high correlations with summer precipitation in the year of growth and the preceeding late summer and negative correlations with summer temperature. In distinctive years (therefore hatched lines are used in Fig. 8), wood anatomical features indicate a delayed onset of the summer monsoon in southern Tibet. Ring width and MLD from the cold-moist subalpine tree limit bear information about winter and summer temperatures. Stable carbon isotopes and ring width data from forest stands at the cold-dry tree limit are, in general, indicators of temperature, but in dry years they are also sensitive to a lack of moisture. The geographical pattern of growth changes in pointer years can help to identify the nature of the triggering climatic event.

The combination of these parameters provides the opportunity to gain insight into seasonal aspects of climate during almost 15 months (early summer of the year prior to growth to late summer of the year of growth). Apart from the reconstruction of single climate elements, such as summer temperature or precipitation, the application of combined multiple proxy data can contribute to the reconstruction of dynamic aspects in circulation patterns. In Tibet, this approach offers the possibility to shed light on shifts in the balance of the competing wind systems of the winter and summer monsoon in periods of changing climate, for example during the Little Ice Age or the Medieval Climatic Optimum.

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