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Dendroclimatological Reconstruction for the Last Sub-millennium in Central Japan

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ABSTRACT

Annually resolved winter temperature and summer precipitation of Central Japan were reconstructed for the past 800 years, back to AD 1177 from an absolutely dated ring-width chronology of *Chamaecyparis obtusa*. This chronology was constructed from 300-year-old living trees and old logs of early modern and medieval origins that exist in hundreds in the Kiso Forest on the foothills of Mt. Ontake (3,063 m a.s.l.). In general agreement with the well established past climatic change in Europe, the reconstructed winter temperature showed three distinctively different phases, i.e. a cooling trend toward the mid 1200s possibly corresponding to the termination of the Medieval Warm Epoch, followed by a long cold spell corresponding to the Little Ice Age till the early 1800s, and then by a conspicuous warming trend continuing up to present.

(Key words: Tree rings, Paleoclimate, Japan)

1. DENDROCHRONOLOGY BUILDING

1.1 Materials

Chamaecyparis obtusa logs representing three different generations were used to construct the present 800-year-long ring-width chronology: old logs of medieval origin that died before AD 1600 but have been preserved naturally on the forest floor, more recent ones of early modern origin and 300-year-old living trees.

An extensive search in the remote forested area of Kiso in Central Japan (Figure 1) resulted in the discovery of old *Chamaecyparis* logs of medieval origin in an alluvial basin at one of the uppermost reaches of the Kiso River (Sweda and Yonenobu, 1990; Sweda *et al.*, 1991; Takeda *et al.*, 1992). The authenticity of their temporal origin is verified by the fact that they are straddled by 300-year-old living trees of the same species that have germinated and grown on top of them as seen in Figure 2.

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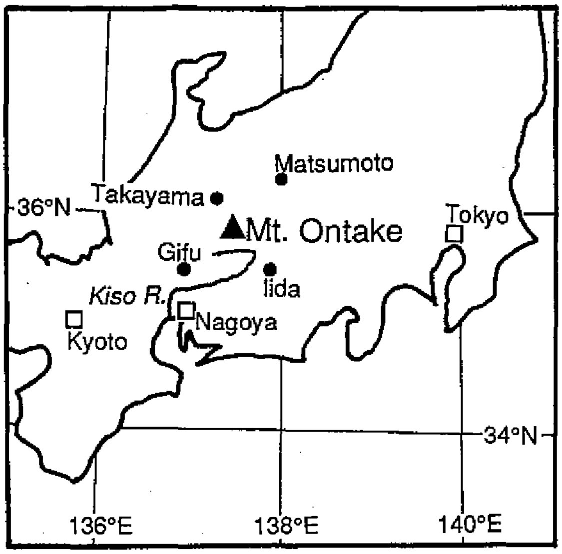

Fig. 1. Central Japan.

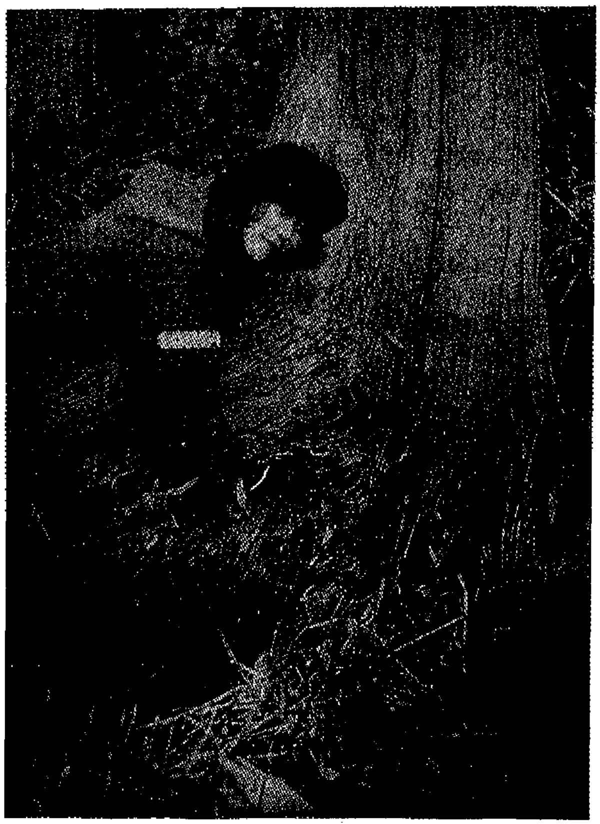

Fig. 2. A medieval log straddled by a 300-year-old living tree.

Log-top natural regeneration itself is not rare in Japan since, being free from shading by a thick cover of dwarf bamboo commonly encountered throughout the country, seedlings germinating on top of dead logs have a better chance of survival than those regenerating directly on mineral soil, especially when the nursery sapwood is moderately rotten and maintains adequate moisture holding capacity. However, old logs such as those used in this study are rather rare since the warm and moist monsoon climate means that they decay quickly, in a matter of several decades or so. Most probably, the cold subalpine climate, with sub-zero temperatures for nearly half the year (Figure 3), shading from sunlight by a dense canopy of 300-year-old *Chamaecyparis* stands (Sweda *et al.*, 1985) and a thick ground cover of bamboo during the height of the growing season when the monthly mean temperature rises to 18°C might also have helped preserve the *Chamaecyparis* wood.

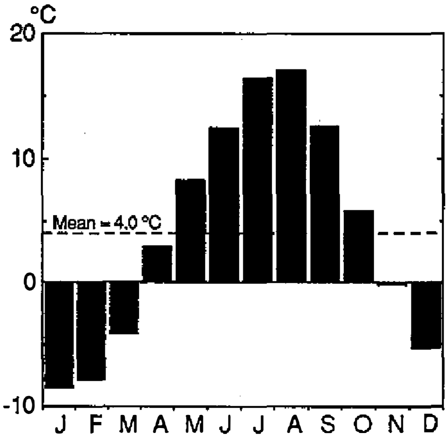

Fig. 3. Estimated mean monthly temperature at medieval log site, Kiso Forest (after Sweda and Yonenobu, 1990).

The existence of the medieval logs suggests that those of more recent origin had a better chance of being preserved. A search for apparently old logs with decaying surface but without old living trees on top, and subsequent crossdating against 300-year-old living trees revealed some 90 logs of more recent origin. These logs are identified here as 'early modern' to distinguish them from those of older and younger generations, though they match the medieval logs and living trees toward the earliest and latest ends respectively of the temporal spectrum of material.

While all the medieval and early modern logs were collected from a more or less protected alluvial basin at an altitude of 1,480 m a.s.l., the modern logs were obtained from living trees growing in the same stretch of 300-year-old *Chamaecyparis* forest but at two different sites some 10 km away to the northwest at an altitude of 1,550 m a.s.l. on the dividing ridge between the Kiso and Hida Rivers. This choice of modern sampling sites was based on an assumption that trees growing on exposed ridges may well have higher climatic fidelity than those in protected sites (Sweda, 1986; Yamamoto *et al.*, 1986).

1.2 Methods

Approximately 80 medieval, 80 early modern and 70 modern logs were collected. These samples were sawn off as disks except for a few medieval logs from which increment cores were taken due to the physical difficulty of sawing. After surfacing and polishing each disk, ring widths were measured with a semiautomatic ring measurement device under microscopic magnification to a precision of 1/100 mm. Two series of measurements in different radial directions were made for each disk. The two series were then averaged, to give an individual tree chronology, which was subsequently standardized to give a series of ring width indices (RWIs). In standardization, a derivative

$$dy/dt = Mk \quad \exp(-kt) \tag{1}$$

of the Mitscherlich's growth equation (Sweda, 1984)

$$y = M\{1 - \exp(-kt)\},$$

where

dy/dt: annual increment of stem radius, i.e. ring width,
y: stem radius,
t: tree age,
M: asymptote of radial growth, and
k: intrinsic rate of growth

was used since this function is known to fit Kiso *Chamaecyparis* well from our previous work (Yamamoto *et al.*, 1986). In the above process of surfacing and measurement, several old logs unable to withstand physical processing and some dendrochronologically inferior samples failing to comply with our prescribed standard of sensitivity and chronology length (100 years or more) were discarded. This resulted in a total of 63 medieval, 74 early modern, and 69 modern logs that constitute the final synthesized standard chronology shown in Figure 4.

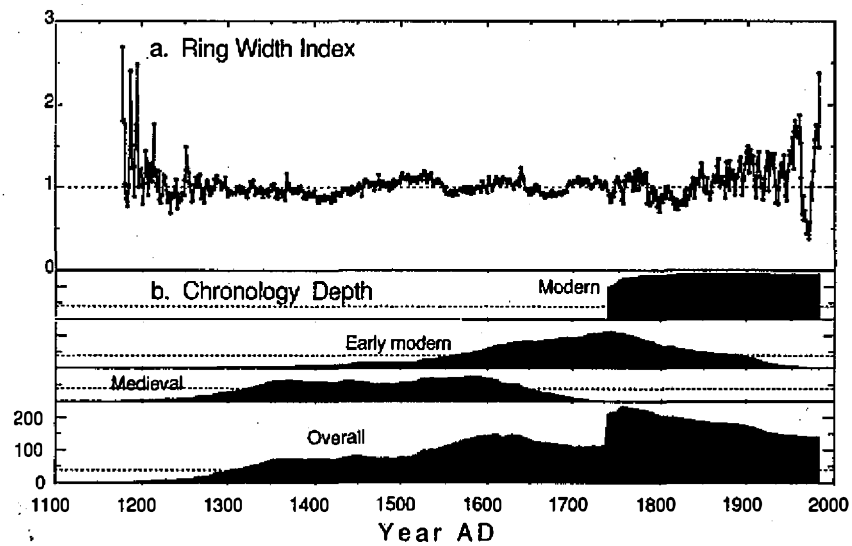

Fig. 4. Standard Dendrochronology for Central Japan. a: Ring width index, b: Chronology depth (sample replication) expressed in terms of incorporated radial measurements. The dotted lines indicate the international requirement for standard chronology, i.e. measurement in two radial directions on each of at least 20 individual trees.

1.3 Synthesized Standard Chronology

The synthesized chronology was established by combining absolutely dated individual tree chronologies of the modern, early modern and medieval logs. The modern portion was first established by simply averaging individual modern chronologies. Then the early modern logs were crossdated against the synthesized chronology, and subsequently added to it. Lastly the medieval logs were dated against the synthesized chronology partially extended with early modern logs, and then incorporated with the other data to complete the 807-year-long standard chronology covering AD 1177 to 1983. The contribution of the three different generations of logs in the synthesized chronology is shown in Figure 4 as chronology depth expressed in terms of number of radial measurements involved.

In the above process of absolute dating, crossdating was conducted visually with disks as well as numerically with ring-width data. In visual crossdating, key years characterized as having particularly wide, narrow, dark rings etc. were identified, and their correspondence among disks was established. In numerical crossdating, a series of running crosscorrelations was calculated using shifting overlaps between the standard chronology and each individual log under examination. The latter was dated according to the timing of culminating cross-correlation. Results from these two different methods showed good general agreement. In cases of disagreement, however, added weight was given to the results of visual comparisons where we had confidence in them, and the sample was discarded where this was not the case.

Before proceeding to dendroclimatic reconstruction, two major characteristics of this standard chronology have to be mentioned. One of them is the variability in ring width which changes in three distinctively different phases: before AD 1300, after AD 1800 and in-between. The high variability in the earliest phase is simply due to small sample size. On the other hand, the equally large magnitude of variability in the latest phase is attributable to the climatic sensitivity of the modern logs, deliberately sampled from sites on exposed ridges. As a matter of fact, the modern logs crossdated extremely well among themselves, whereas this was not the case for the older logs. Individual old logs showed variability of similar magnitude to that of modern logs, but having had grown in a protected basin, synchronous climatic component of variability was rather weak in comparison with randomly occurring inter-tree competition component, making the synthesized chronology complacent in the phase between AD 1300 to 1800. The other characteristic, or more aptly flaw from dendroclimatic point of view, in the synthesized dendrochronology is the depression spanning the two decades after 1960. This might be attributable to either a major typhoon in 1959 or the country-wide air pollution of the 1960s or both. In any case, this portion doesn't represent climatic variation per se and was excluded from the following dendroclimatic analysis.

2. DENDROCLIMATIC RECONSTRUCTION

Two major difficulties were encountered in the dendroclimatic reconstruction: the sharp recent growth depression referred to above, and the choice of weather stations with which to correlate the standard dendrochronology.

The first difficulty relates to the large non-climatic variability associated with this depression, which occurs at a crucial time during the limited period of past instrumental climate observation. The data can either be truncated, left as it is, or corrected in some way or another. Of these three possibilities, we have opted for the first, since it seemed most sound and appropriate for this preliminary climatic reconstruction. However, it resulted in a loss of a precious 20 out of only 80 years of instrumental climate observations available concurrently with the standard chronology.

The second difficulty is associated with the fact that, of four weather stations within an 80 km range surrounding Mt. Ontake, no one station represents the tree-ring chronology location particularly well. Again various approaches might have been adopted, such as choosing the most representative station, or taking a seasonally differentiated average of the stations depending on the seasonal weather pattern over Japan etc. Again, the most straightforward alternative was adopted, and the instrumental records of monthly mean temperature and monthly precipitation from the four stations were simply averaged. As a result, the following climatic reconstruction is based upon a mere 56-year-long monthly climate data set running from 1904 to 1959 inclusively, the beginning limited by the availability of climate record and the end by the inadequacy of the dendrochronology.

2.1 Response Function Analysis

According to our field observations, tree growth in Kiso begins in April and ends by October, suggesting an appropriate definition of the growth year as beginning in November and ending in the following October, therefore preceding the calendar year by two months as shown in Figure 5.

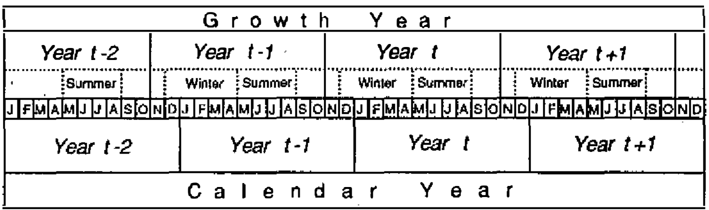

Fig. 5. Definition of growth year.

A preliminary analysis using simple linear correlation (Figure 6) indicates that annual tree growth (*RWI*) tends to be best correlated with temperature during winter months (December to April) and precipitation during summer months (May to August) than with any other combination of climatic factors and seasons as examined for up to three years prior to the growing season (Sweda 1992). Thus, as a first step in determining a response function, multiple linear regression of monthly winter temperatures and summer precipitation on *RWI* was performed and the results tested for significance of the partial and multiple correlations. In the t- and F-tests of the correlation coefficients (Afifi and Clark, 1984), involving a total of 27 predictor variables, i.e. five monthly mean temperatures and four monthly precipitation annually for three years, the significance of the partial correlations proved to be rather inconsistent, whereas the multiple correlation was highly significant. This result indicates that the proposed model had too many predictor variables. Thus, in the subsequent analysis, the climatic variables were reduced from monthly to seasonal values. Then the response function of the form:

$$RWI = aRWI' + bRWI'' + cTw + dTw' + eTw'' + fPs + gPs' + hPs'' + i \quad (2)$$

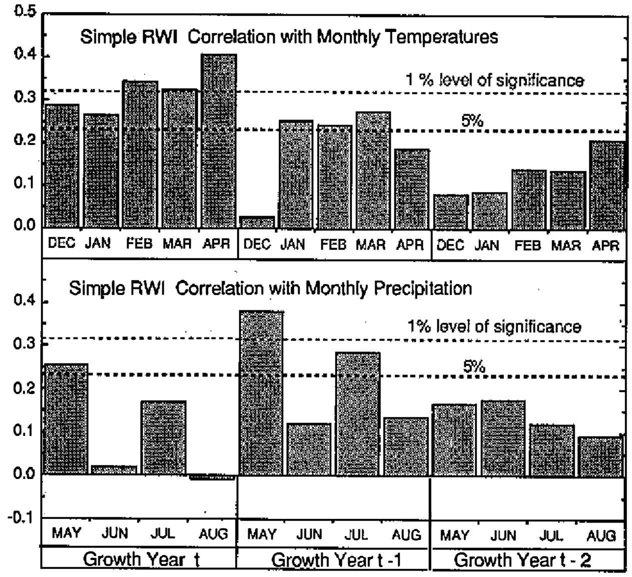

Fig. 6. Response of tree growth to monthly climatic values.

where *RWI*: the ring width index in growth year t,

Tw: winter (December-April) mean temperature of growth year t,

Ps: summer (May-August) precipitation of growth year t, with prime (′) and double prime (″) indicating the previous growth year (t-1) and the year before that (t-2) respectively, and

$a \sim i$: the regression coefficients,

was iteratively reduced by eliminating non-significant predictor variables in the t-test of significance on individual partial correlation coefficients. As shown in Table 1, the significant variables turned out to be the first-order autocorrelation term, winter mean temperature of the same growth year *Tw*, and total summer precipitation of the previous growth year *Ps*′.

In Figure 7 the *RWI* reconstructed according to this reduced multiple regression (Model 2) is shown in comparison with the observed counterpart. The agreement is satisfactory as would be expected given the highly significant multiple correlation in Table 1.

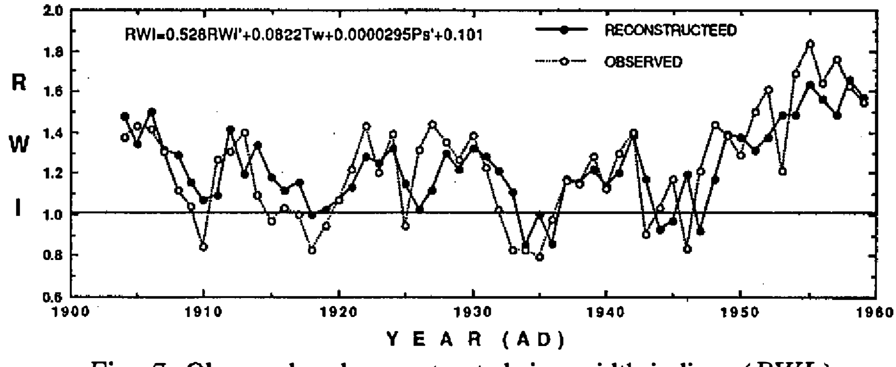

Fig. 7. Observed and reconstructed ring-width indices (*RWIs*).

Table 1. Iterative Determination of Responce Function.

Predictor Variables	Correlation Coefficnent		
	Simple Corr.	Partial Correalation	
		Model 1	Model 2
AC1	0.663 **	0.443 **	0.589 **
AC2	0.495 **	0.088 ns	-
Tw	0.516 **	0.314 *	0.318 *
Tw'	0.334 **	-0.064 ns	-
TW"	0.223 *	-0.062 ns	-
Ps	0.163 ns	-0.079 ns	-
Ps'	0.383 **	0.282 *	0.290 *
Ps"	0.251 *	0.031 ns	-
Multiple Correlation		0.753 **	0.748 **

**: significant at 1% level, *: significant at 5% level, and ns: non-significant in t-test of significance for simple and partial correlation coefficients and F-test for multiple correlation coeficents.

2.2 Transfer Function Analysis

The dependence of current *RWI* on winter temperature of the same growth year and the *RWI* and summer precipitation of the year directly preceding growth indicates that these two climatic variables can be reconstructed from current and preceding *RWIs*. Accordingly, transfer functions of the form:

$$\text{winter temperature} \qquad Tw = aRWI + bRWI' + c \tag{3}$$

$$\text{summer precipitation} \qquad Ps' = a'RWI + b'RWI' + c' \tag{4}$$

were calculated and tested. In the above multiple regression, the coefficients and error term for precipitation reconstruction were primed ($'$) to indicate that they should be different numerically from those for temperature reconstruction, but not in the sense according to which independent variables are primed in (2). As shown in Table 2, the winter temperature and summer precipitation reconstructed by transfer functions based on the whole period of concurrent observations revealed satisfactory multiple correlation with the observed counterparts. For more rigorous verification, the whole period of concurrent observations was divided into early and late halves, and cross F-tests of significance were conducted, in which the climatic estimates reconstructed from each half of the observation were tested against the observed climate over the other half. Although the transfer function based on the late half scored satisfactory, the calibrated over the early half failed to verify significantly as shown in Table 2. A t-test of the significance of the partial correlation (not given in the table) revealed that the contribution of *RWI'* in multiple regressions (3) and (4) was low, indicating that further reduction in the independent variables was appropriate.

After removing *RWI'* the same verification procedure was repeated for transfer functions of the form:

$$\text{winter temperature} \qquad Tw = aRWI + b \tag{5}$$

summer precipitation $$Ps' = a'RWI + b' \qquad (6)$$

These are no longer multiple regressions but simple ones. The verification is given in Table 3. The transfer function based on the early half again failed to verify significantly, while the correlation based on the late calibration proved to be significant at 1% level.

Table 2. F-test of significance on transfer funcitons
$Tw=aRWI+bRWI'+c$ and $Ps'=a'RWI+b'RWI'+c'$

Climatic Factor	Transfer Function by	Verification with	Mult. Corr. Coef.	Calculated F
Temp.	Whole Period		0.520	9.821 **
	Early Half	Late Half	0.358	1.838 ns
	Late Half	Early Half	0.637	8.536 **
Prec.	Whole Period		0.393	4.841 *
	Early Half	Late Half	0.255	0.869 ns
	Late Half	Early Half	0.537	5.065 *

**: significant at 1% level, *: significant at 5% level, and ns: non-significant

Table 3. t-test of significance on transfer functions.
$Tw=aRWI+b$ and $Ps'=a'RWI+b'$

Climatic Factor	Transfer Function by	Verification with	Simple Corr. Coeff.	Calculated t
Temp.	Whole Period		0.516	4.427 **
	Early Half	Late Half	0.277	1.470 ns
	Late Half	Early Half	0.606	3.885 **
Prec.	Whole Period		0.382	3.037 *
	Early Half	Late Half	0.242	1.272 ns
	Late Half	Early Half	0.525	3.145 *

**: significant at 1% level, *: significant at 5% level, and ns: non-significant

2.3 Validity of Climatic Reconstruction

The above discussion indicates that the present dendroclimatic reconstruction is not fully valid from a rigorous statistical standpoint. However, judging from the satisfactory agreement between the observed and reconstructed *RWIs* (Figure 7) and the overall agreement between the observed and reconstructed climates (Table 3), we have a good reason to believe that the validity of climatic reconstruction might be improved sufficiently by overcoming the difficulties mentioned earlier.

The major difficulty of limited climate data (only 56 years) could be largely overcome by correcting the recent section of the chronology. It is worth mentioning here that the depressed growth in the apparent chronology is inversely correlated with the pattern of total sulfur oxide emission in the country over the same period. Further experimentation in the choice of weather stations and of seasons to be predicted would also improve the power of transfer functions.

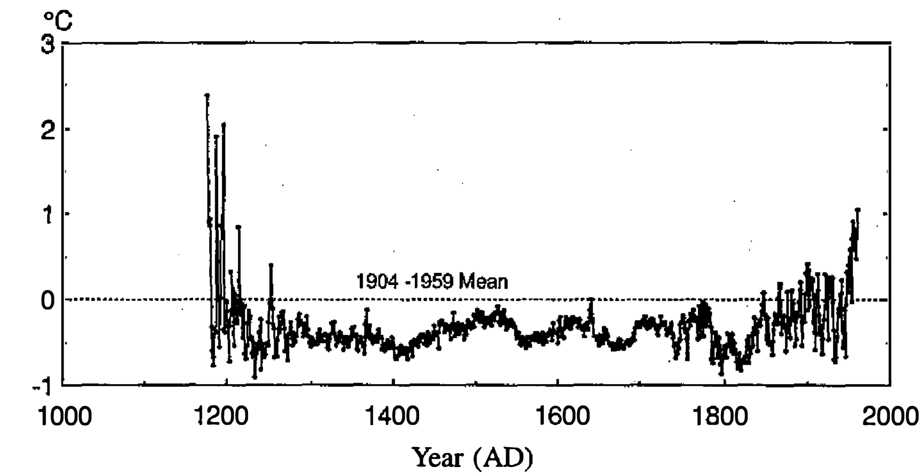

Fig. 8. Reconstructed winter (December-April) temperature, as deviations from the 1904-1959 observed mean.

Meanwhile, temperature and precipitation reconstructions based on transfer functions (5) and (6) are shown in Figures 8 and 9. These extend over the entire period of available ring-width chronology except for the latest end of the chronology where the non-climatic growth depression will surely distort reconstruction. The reconstructions are expressed as departures from the respective period means, i.e. 1904 to 1959 for temperature and 1903 to 1958 for precipitation. These reconstructions, looking so similar to each other, indicated the limitation of climatic reconstruction from the single independent variable *RWI* with simple regressions (5) and (6). Estimates for two variables from one inevitably look alike. Though increase in temperature should generally result in increases in evaporation, and eventually in precipitation, this is rather extreme.

In view of higher and more consistent correlation of *RWI* with temperature than with precipitation as seen in Figure 6 and Tables 1 through 3, it would be reasonable to consider

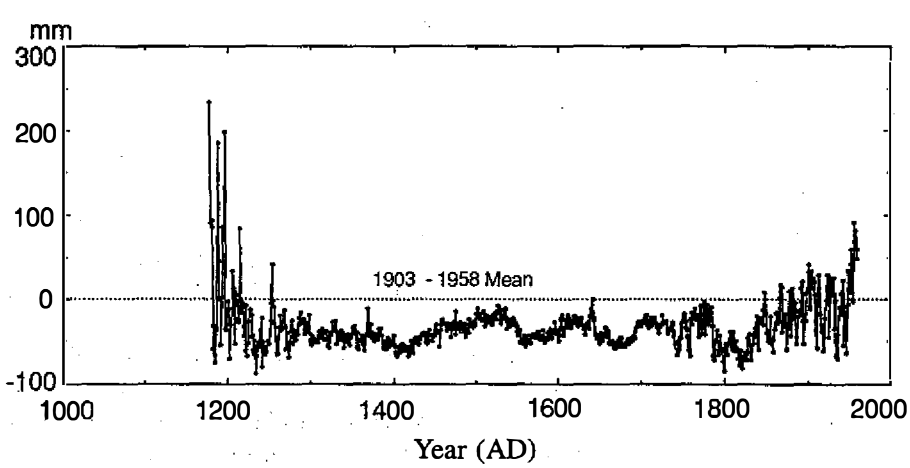

Fig. 9. Reconstructed summer (May-August) precipitation, as deviations from the 1903-1958 observed mean.

temperature reconstruction more realistic than precipitation counterpart. The reconstruction can be further improved by incorporating more independent variables such as wood density and earlywood/latewood ratio that may characterize other aspect of variability in tree growth.

Another inadequacy with the present reconstruction results from non homoscedasticity of the original tree-ring chronology mentioned earlier. In other words the complacency in the medieval and early modern chronology has made the corresponding climatic estimates complacent in comparison with the modern portion, which may not have been the case in reality. Correction for homoscedasticity of the original chronology by weighing with variance and sample size will certainly improve the reconstruction.

3. DISCUSSION

In spite of some shortcomings discussed in the preceding section, the reconstructed climate, especially temperature (Figure 8) generally agrees with the past pattern of climatic change inferred from European data sets (e.g. Bradley and Jones 1992, Mörner and Karlén 1984). The three distinctive phases, i.e. the cooling phase ending in the mid 1200s; the cold phase lasting until the mid 1800s, with a period of climatic minimum toward its end; and a warming phase continuing up to the present may well correspond respectively to the termination of the Medieval Warm Epoch, the Little Ice Age and the global warming trend after the Industrial Revolution.

Particularly noteworthy would be the general warming trend since the mid 1800s and more acute warming since the mid 1900s in association with the greenhouse effects of increasing atmospheric carbon dioxide (Neftel *et al.* 1985, Bacastow and Keeling 1981). Most probably the former warming trend may correspond with some lag to increased CO_2 emission from deforestation and industrialization in Europe and North America since the Industrial Revolution, while the latter to accelerated use of fossil fuels by developed countries as well as industrial emergence and development of Asian countries, both seemingly triggered by the termination of the World War II (Houghton and Woodwell 1989).

Some of the acute cooling may correspond to major volcanic eruptions, of which Katla in 1179, and Laki and Asama in 1783 are the most pronounced. No obvious relationship was found between the reconstructed temperature and solar minima such as Wolf, Spörer and Maunder, however, the tree-rings formed in these periods were complacent and devoid of significantly characteristic rings useful for visual crossdating.

To our knowledge, this is the longest absolutely-dated and annually-resolved dendroclimatic reconstruction in Japan and possibly in Monsoon Asia. A more intensive search for older logs in the field may well result in an extension of the ring-width chronology and climatic reconstruction by a couple of hundred years. The quality of the dendroclimatic reconstructions would be improved by the use of data for other tree-ring parameters such as wood density, and early/late wood ratio etc.

One area with potential to produce similar reconstructions to those described here is undoubtedly Taiwan where *Chamaecyparis formosensis* over a thousand years in age are still available in relative abundance. Similar work would also be possible with similarly old *Cryptomeria japonica* found in Yakushima Island, Southern Japan. Though similar work might also be possible in the rest of Monsoon Asia, the prospect are not so good. Chronologies would be significantly shorter because of the limited availability of good dendrochronological materials in temperate zone, where forests have been depleted due to the long history of heavy human habitation, as well as in subtropical zone where a higher proportion of hardwood species makes chronology construction more difficult.

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