**TREE-RING RESEARCH,** *Vol. 59(2), 2003, pp. 81–98*

# TESTS OF THE RCS METHOD FOR PRESERVING LOW-FREQUENCY VARIABILITY IN LONG TREE-RING CHRONOLOGIES

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## ABSTRACT

To preserve multi-centennial length variability in annual tree-ring chronologies, the Regional Curve Standardization (RCS) method calculates anomalies from a regionally common, non-climatic age-trend function. The influence of various factors on the estimation of the regional curve (RC) and resulting RCS-chronology is discussed. These factors are: the method of calculating anomalies from the age-trend function, estimation of the true pith offset, the number of series used, species composition, and site characteristics. By applying RCS to a collection of millennium-length tree-ring data sets, the potential and limitations of the RCS method are investigated. RCS is found to be reasonably robust with respect to tested factors, suggesting the method is a suitable tool for preserving low-frequency variance in long tree-ring chronologies.

*Keywords:* dendroclimatology, tree rings, RCS method, low frequency, long-term chronology, climate.

## THE LOW FREQUENCY DESIDERATUM

Low-frequency climate variations in multi-centennial tree-ring chronologies can be difficult to preserve. Even when using chronologies of ring width (TRW) or maximum tree-ring density (MXD) of 500 or more years, the chronologies still lack significant low-frequency variations greater than interdecadal timescales (overview in Schweingruber 1996). The lack of multi-centennial, timescale variability in such chronologies results from a variety of causes, including the natural case where climate forcing on tree growth approximates a white noise process (*e.g.* precipitation). However, when multi-centennial changes in climate (*e.g.* temperature) do affect tree growth, a climatically sensitive tree-ring chronology from such trees should also reflect these same changes. So, why is it so difficult to detect multi-centennial climate variability in such series? The most common reason relates to the way that the raw tree-ring measurements are detrended to create the site or regional tree-ring chronology used for climate reconstruction (Briffa *et al.* 1990; Briffa *et al.* 1992).

Long tree-ring chronologies are often built by crossdating individual TRW or MXD time series from living trees with those from historic or subfossil wood samples to extend the living tree information further back in time. With sufficient overlap over time, vis-à-vis a common climate signal, both dead and living trees will contain the same interannual variations permitting the material to be linked exactly in time. This "crossdating" of samples allows very long chronologies (*e.g.* >1,000 years) to be developed even if the segment lengths contributed by any single series in the chronology is much shorter (*e.g.* 250 years) (Douglass 1929).

Every tree-ring time series, whether it is based on TRW or MXD, contains some non-climatic variations. This "noise" can be caused by site-related effects (*e.g.* competition and disturbance) or biological effects (*e.g.* aging). As a consequence of integrating biological and ecological impacts within the measured parameter, TRW or MXD, variability in the resulting chronology will often depart from variability associated with climate. This departure from climate is often systematic and persistent over time. Such low-frequency, age-related trend is considered noise for the purpose of climate reconstruction and must be eliminated before averaging the individual tree-ring series from a site or region into a long mean chronology (Cook and Kairiukstis 1990; Fritts 1976). The process of detrending (or standardization) is fraught with uncertainty especially in short or young tree-ring series. When low-frequency signals caused by climate approach or exceed the lengths of the individual tree-ring series used in long tree-ring chronologies, it may be impossible to differentiate the low frequency climate signal from the low-frequency noise (non-climatic signal). Therefore, it is much easier to preserve interannual or interdecadal climatic signals, in long tree-ring chronologies, with more certainty.

## PRINCIPLES OF RCS AND OPEN QUESTIONS

One of the more advanced methods of tree-ring detrending, used to preserve multi-centennial variability in tree-ring chronologies, is the Regional Curve Standardization (RCS) (Mitchell 1967; Becker *et al.* 1995; Briffa *et al.* 1992, 1996). Recently, RCS has been successfully applied to several large tree-ring data sets in an effort to preserve as much low-frequency climate variability as possible (Briffa *et al.* 1992, 1995; Cook *et al.* 2000; Esper *et al.* 2002; Naurzbaev *et al.* 2002).

A schematic example of RCS using three 100-year old, raw-ring-width series (T1, T2, T3) is shown in Figure 1A. The dates of the outermost rings of the trees are A.D. 1899 (T1), A.D. 1950 (T2) and A.D. 2000 (T3), and their placements in time have been determined by crossdating. Thus, the total chronology covers the period A.D. 1800–2000, a doubling of the individual segment lengths. RCS begins with aligning the individual tree-ring series by cambial age. Meaning, the innermost rings of T1, T2 and T3 are set to a biological age of 1 (Figure 1B). RCS assumes then that such "age-aligned" time series collectively describe the functional form of the overall, age-related, growth trend typical for the species, on a given site, in a given region. Thus, the gross, collective trend only reflects age-related, biological noise. The average behavior of this, now-assumed, non-climatic noise can be estimated by calculating its mean value. Such a mean biological age trend forms what is called the "regional curve" (RC) (Figure 1B). Departures by the raw data from the RC are interpreted as departures related to climate or some other non-biologically induced forcing (Briffa *et al.* 1996). The new RC growth anomalies, for T1, T2 and T3, are re-aligned by calendar year in Figure 1C. The last step, not shown in this example, is the calculation of a mean chronology from the T1, T2 and T3 anomalies to produce the final RCS-chronology.

It is clear from the example that more than three trees are needed to establish a RC that might model the ideal age-related noise in a particular collection of trees. Just how the performance of the RCS method changes with sample depth is not known. There are other questions that relate to the ability of RCS to reconstruct low-frequency climatic variation. In this paper we address some of the most basic of these by experimenting with the

RCS method on a number of millennium-length tree-ring data sets. The questions asked are:

- Is there a difference between TRW and MXD data when used in RCS?
- What is the influence of the method chosen to compute departures of anomalies, on the resulting RCS chronology?
- What is the influence of "pith offset", the estimation of the trees true biological age, on the RCS chronology?
- What is the influence of sample depth?
- What is the influence of species composition?
- What is the influence of site composition?

## TREE-RING WIDTH AND MAXIMUM DENSITY DATA

In dendrochronology the inherent statistical properties and treatment of TRW and MXD are different. Figure 2 compares two chronologies, TRW and MXD, from the same *Pinus sylvatica* trees growing on the island of Gotland, Sweden (Bartholin and Karlén 1983; Bartholin 1984, 1990). Each chronology is a composite of living and dead material with a maximum sample depth of 22 series occurring in the late 17th and 18th Centuries. The overall chronology extends back to A.D. 1127 and ends in A.D. 1987. Average TRW and MXD at Gotland are 0.81 mm and 0.90 g/cm$^3$, respectively. The average segment length (SL) of all series is 131 years making it almost impossible to preserve centennial time-scale variability if the series were detrended and averaged by standard methods (Cook *et al.* 1995). The age structure of this test dataset will affect the sample depth over time and the length of the resulting RC. Also important for RCS, as for all other standardization methods, is the growth pattern of the individual series. Many of the TRW series start with high values then decline with increasing age. TRW values range from 5 mm to nearly zero. The MXD values do not decline strongly with age, they do not fall below 0.30 g/cm$^3$, and their range is less than 1 g/cm$^3$. The properties of the Gotland data set are not atypical (Bräker 1981). In general, raw MXD series have smaller variances with less age-related trends. Values higher than 1.20 g/cm$^3$ and below 0.30 g/cm$^3$ are unusual.

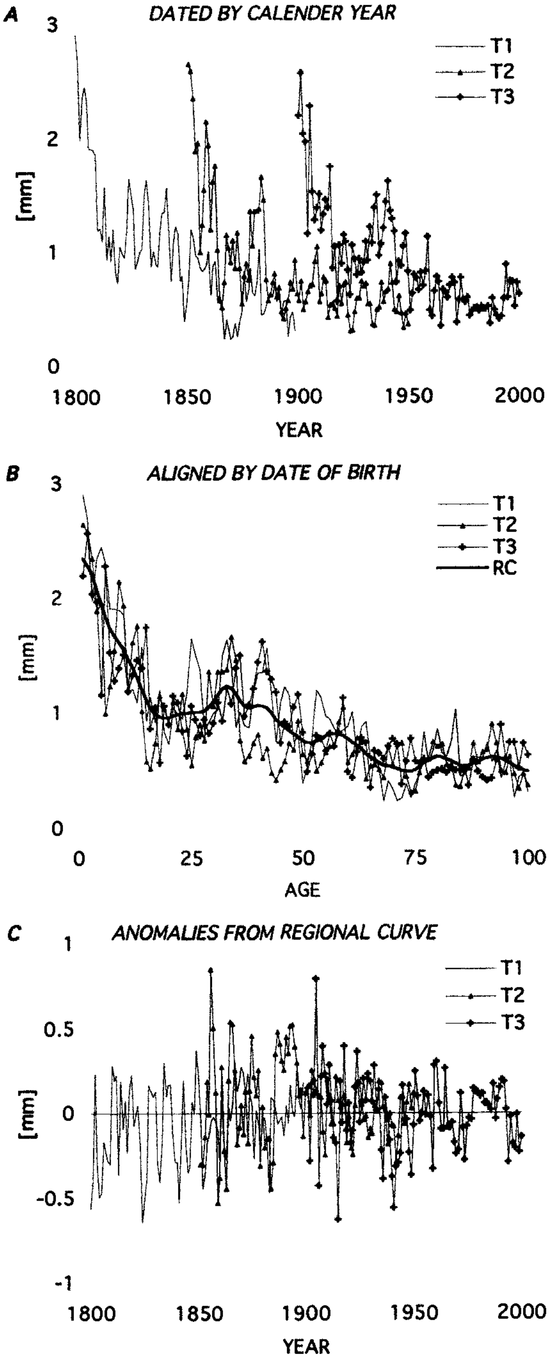

**Figure 1.** Schematic example of the RCS method.

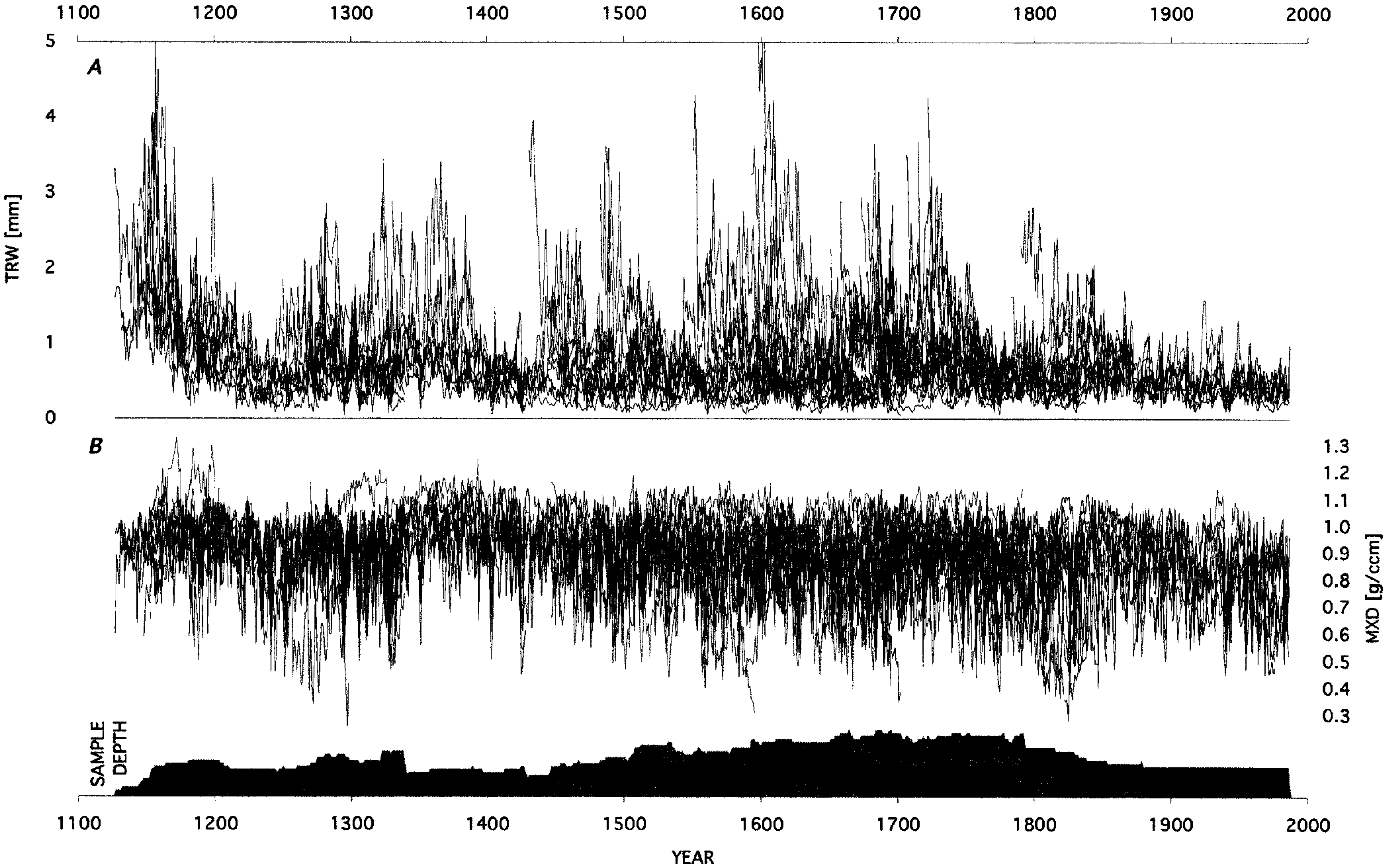

**Figure 2.** 86 individual, raw TRW (A) and MXD series (B) from Gotland, Sweden. Colored shades indicate numbers of series from living (dark) and dead trees (light).

Analyses of the raw tree-ring data, whether living or dead, can help decide if subsamples of trees, growing in different time periods, belong to the same "biological-growth" population, a necessary precondition for applying the RCS method. By "biological-growth" population we mean that the same basic functional form of biological growth exists in all trees regardless of the time period in which the trees grew. The absolute levels of growth may differ, hopefully caused by changes in climate, but the shape of the trees' biological growth curves must remain more or less the same. It is crucial for the RCS method to first classify all possible biological-growth curve populations in this manner. If available, this classification should also consider the meta-information about the site. Further comparisons of the raw data with other long-term, proxy climate estimates may also be useful in detecting unwanted, non-climatic variation. Here we suggest analyzing (i) the raw chronologies, (ii) the mean curves after age-alignment, and (iii) the relationship of the mean measured parameter values versus the age of individual series in attempts to identify possible sub-populations (Figure 3).

In the case of the Gotland data the first obvious subdivision is the separation of living vs. dead trees. Both raw TRW and MXD chronologies from living trees decline through time (Figure 3A). During the common period the chronologies from living trees have a higher mean value than the chronologies from the dead trees. This difference is particularly obvious in the MXD data, and less obvious in the TRW data. It is caused by the inclusion of material of different cambial ages. Over the period in common, the mean chronology from dead material is composed mostly of old, slow-growing trees and the mean chronology from living material is predominantly composed of young, fast-growing trees (see also Figure 5A). Differences, such as slope and level, between living and dead trees, almost disappear after aligning the series by cambial age, indicating that living and dead tree data indeed belong to the same basic biological-growth population (Figure 3B).

Another proof for the existence of a single, Gotland biological-growth population, is the characteristically homogenous decline of the average TRW with increasing series length (SL) (Fritts 1976). A corresponding analysis of MXD, generally, does not show such a relationship. Nevertheless, it is still necessary to search for such relationships in all data to detect possible sub-populations.

Finding evidence for more than one biological-growth population, in the manner introduced above, does not necessarily mean that RCS cannot be used. We recommend this testing because it can provide insights into the behavior of the resulting RCS chronologies and consequently interpretations from those chronologies. In general, the effect of different biological-growth populations on the resulting RCS-chronologies depends strongly on the calendar periods covered by any population's departure from the RC. If, for example, the overlap between populations is short (*e.g.* one starts A.D. 1850, another ends A.D. 1880), the potential bias on the RCS-chronologies, from 1850–1880, could be quite large.

## TESTING THE RCS METHOD

In this paper we estimate the RC by first calculating the bi-weight robust mean (Cook and Kairiukstis 1990) of the age-aligned series, followed by fitting a cubic smoothing spline with a 50% frequency-response cutoff at 10% of the series length (Cook and Peters 1981). Anomalies from the RC are calculated using ratios, residuals and residuals after power transformation (PT) (Cook and Peters 1997). The variances of the resulting RCS-chronologies are adjusted for changing sample depth by utilizing the sample depth information and the average correlation between series (Osborn *et al.* 1997).

### Influence of Calculation Method

There exist two fundamentally different methods of calculating anomalies from a fitted growth curve: residuals and ratios (Fritts 1976; Cook and Kairiukstis 1990). In the case of RCS, the fitted growth curve is the RC spline, reflecting the overall, age-related behavior of all sampled trees in a given region. In addition to residuals and ratios, we also test the performance of a combination of

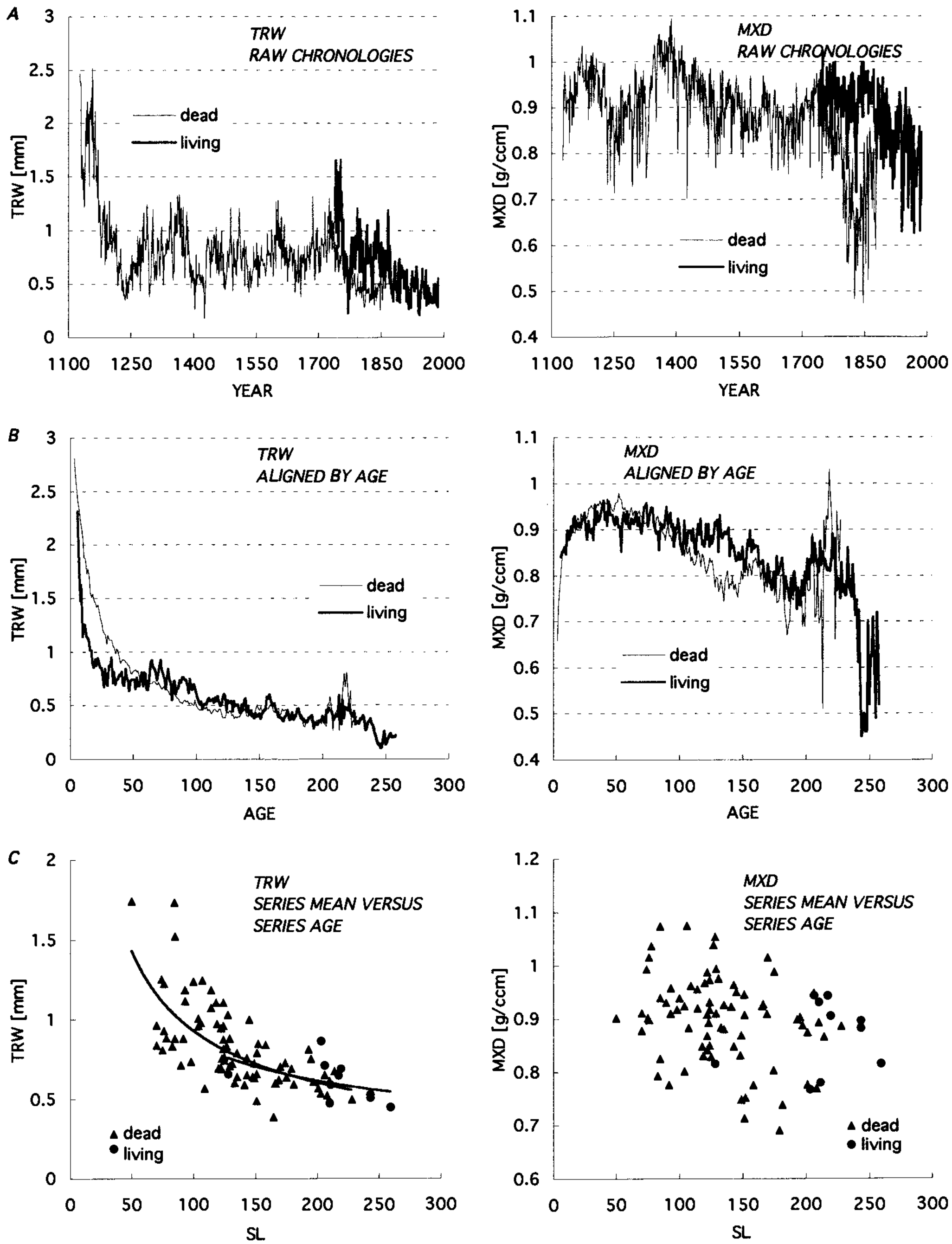

**Figure 3.** Raw TRW and MXD chronologies (A), mean curves after age-alignment (B), and scatter diagrams of the series mean versus segment length (C). All diagrams differentiate between dead and living trees.

residuals together after adaptive power transformations have been applied to the data (Cook and Peters 1997). Note that these calculation methods (residuals, ratios, and PT plus residuals) were developed for standardization procedures where each original series is detrended individually by its own unique growth curve. Second, residuals and ratios handle changing variance of raw TRW series in entirely different ways (Bräker 1981). Residuals without PT do not change the heteroscedastic nature of raw TRW series, a benefit that generally occurs by calculating ratios. The power transformation, as introduced by Cook and Peters (1997), stabilizes changing variance prior to the calculation of residuals.

When applying these different calculation methods to the Gotland TRW data (Figure 4) the growth levels, trends and variances of the resulting RCS-chronologies are similar in most periods since A.D. 1127, *i.e.* the effect of the calculation method is small. However, significant differences are recorded in the modern period since the early 19th Century. Calculating ratios results in higher chronology levels after A.D. 1830 with increased variances; the PT plus residuals result in lower chronology levels, occasionally below the long-term average, with decreased variances; and indices from residuals perform somewhere in between. These differences result from the use of PT and the position of the modern series (Figures 4B and 4C) with respect to the RC spline.

For ratios, when the RC spline of the age-aligned series gets close to 0.5 mm, in this example, the resulting indices can overestimate "real" growth levels and their variance may have a positive bias (Cook and Peters 1997) (Figure 4B). For PT plus residuals, applying the PT increases the spread of all series, *i.e.* the series are more widely distributed around the RC spline (Figure 4C). This change is caused by the average power of the Gotland TRW data (0.352) indicating a strong spread-versus-level relationship (Cook and Peters 1997). In this example, the position of the data from living trees has been most severely affected. After applying PT, more of the modern series fall below the RC (Figure 4C) which systematically devalues these series in relation to the older series and drives the lower chronology level after A.D. 1830 (Figure 4A). These effects cannot be studied with MXD data because the power of MXD series is close to 1. For residuals, the fundamental penalty of not stabilizing variances of heteroscedastic TRW series, is of minor importance to the RCS-method (Bräker 1981). This is because RCS is usually computed for very long data sets from living and dead trees. After converting the series back to calendar years, the persistently high-variance periods of young trees and the low-variance periods of old trees are evenly distributed over the entire chronology length. In other words, the RCS-chronology averages juvenile and adult trees over every calendar year except in the 20th Century when the Gotland trees age synchronously (Figure 5A).

Results from both methods (residuals and ratios) are often similar and favoring one over the other is up to the experimenter. The purpose of showing the different calculation methods in such detail is (i) to demonstrate the impact on the resulting chronologies and (ii) to recommend comparisons. For the Gotland TRW data, the resulting three different chronologies do behave differently in the late 19th and 20th Centuries. Such differences would influence one's interpretation of the climate history represented by these chronologies.

## Influence of Pith Offset

Another open question is the influence of the pith offset (PO) estimate and its uncertainty on RCS-chronologies. PO is the difference in years between the innermost measured ring, of a core or disk sample, and the actual first year of growth of the tree. PO is greater than zero in samples that miss the pith and, generally, larger for old or big trees. Estimating PO from samples above 1.3 m from the base also introduces significant error. Attention must be given to estimating PO from samples of dead trees. PO is estimated with the highest precision by interpolating the distance to the geometric center of a tree, using the curvature of the innermost rings of a sample, then estimating the number of rings that would fill the missing segment. The number of years estimated to the pith is based on the growth rate after the missing segment (Bräker 1981). Therefore, the same-sized

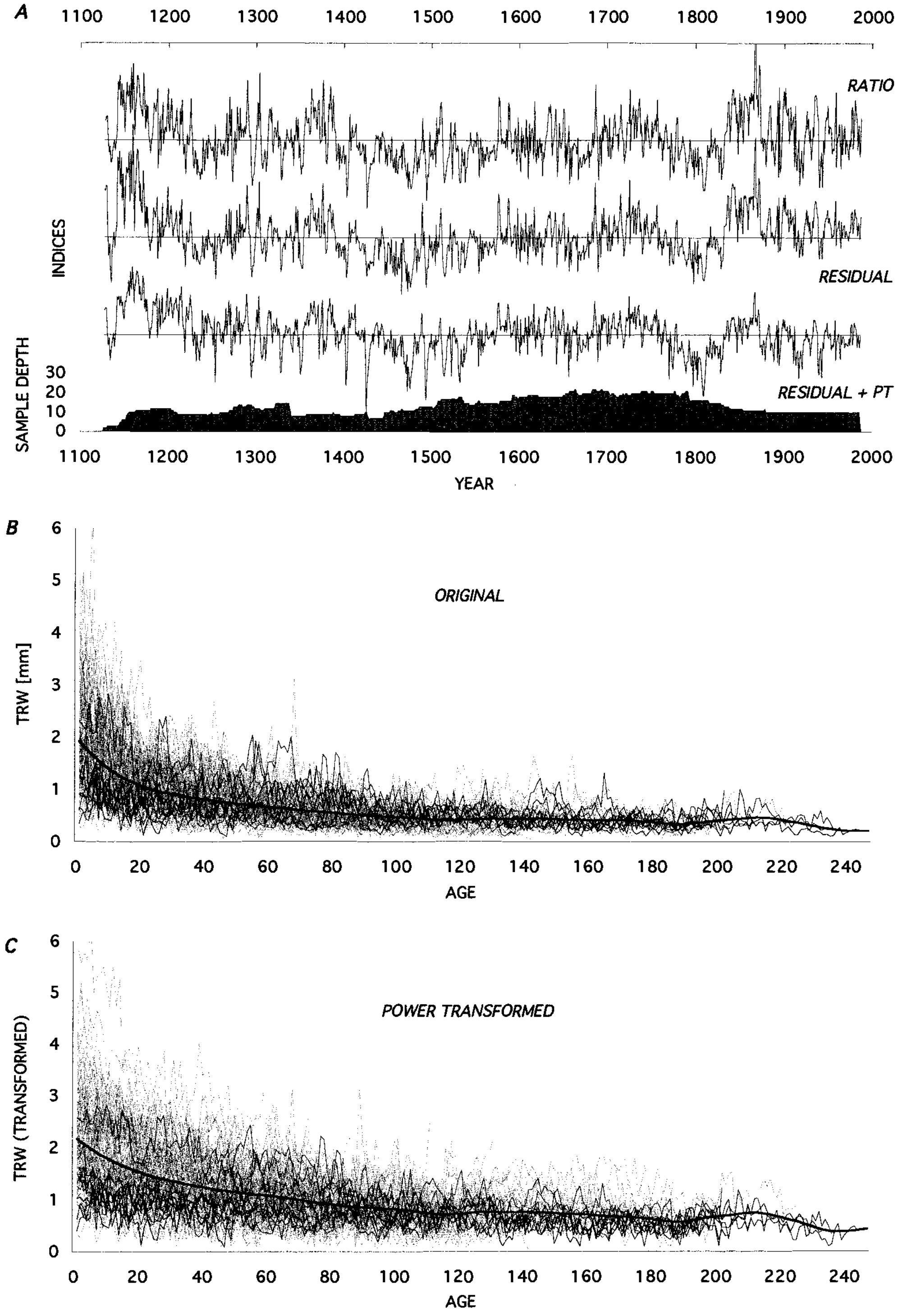

**Figure 4.** RCS-chronologies calculated using ratios, residuals and power transformation plus residuals (A). (B) shows the raw, age-aligned series and (C) the power transformed, age-aligned series. Series from living trees are highlighted black. Thick curves are the regional curve splines.

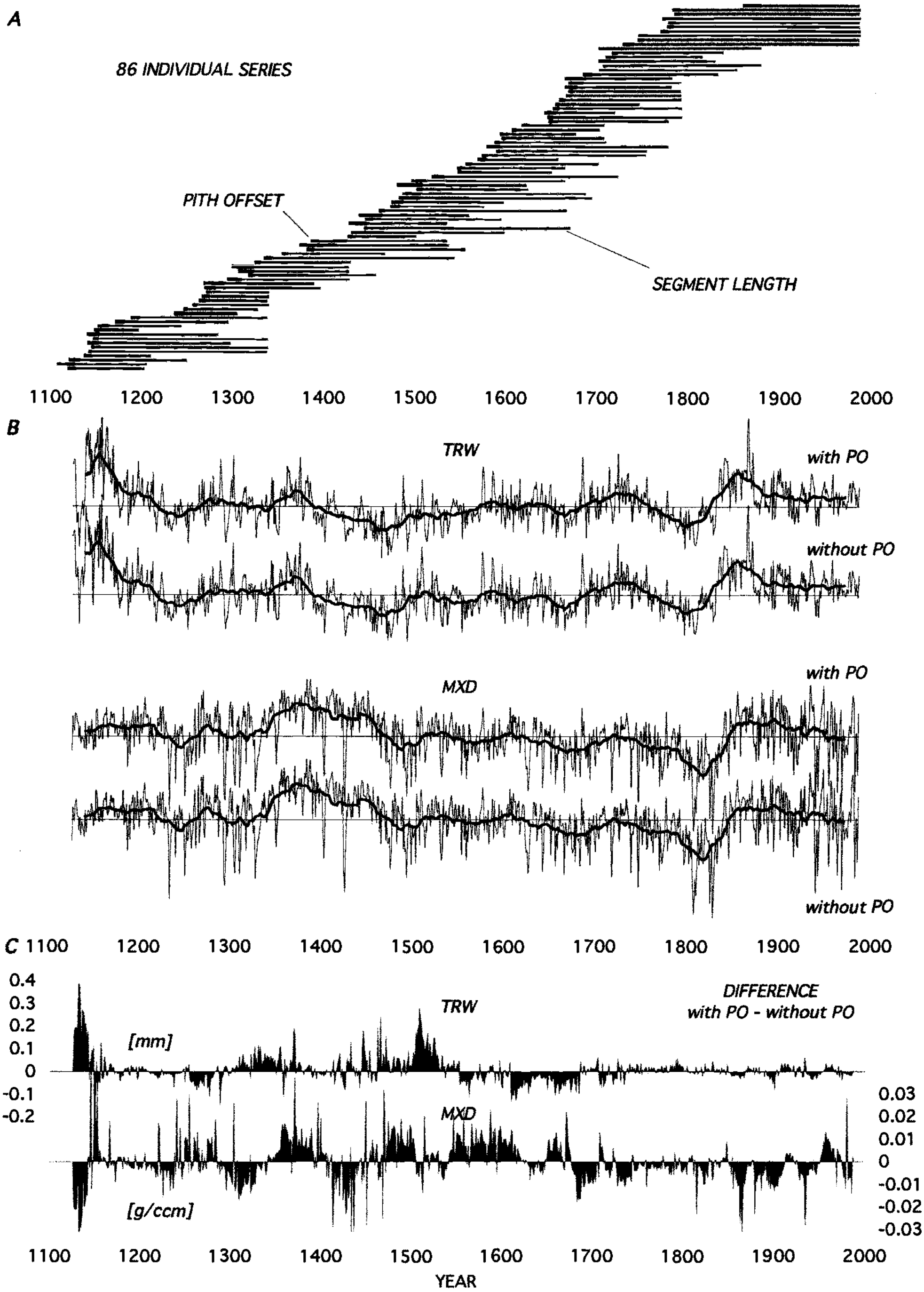

**Figure 5.** Segment lengths (gray) and pith offsets (black) of individual series from Gotland (A). (B) shows the TRW and MXD chronologies calculated with and without pith offset, and (C) the annual differences between the chronologies.

missing segment from a fast-growing tree will have a smaller PO then an equally-sized missing segment from a slow-growing tree. Average PO, in the 86 series Gotland dataset, is 11 years with a maximum of 40 and a minimum of 2 years (Figure 5A). No single core sample includes the pith. PO is important to RCS because it influences the behavior of the RC and the resulting RCS-chronology. Consequently, the phrase "alignment by cambial age" is not accurate without some reasonable estimate of PO.

To illustrate the influence of PO on RCS we developed four RCS chronologies from the Gotland dataset, two for both the TRW and MXD data. One chronology, for each measured parameter, was developed without any PO information whereas the second includes PO estimates (Figure 5B). Visually comparing all four chronologies there doesn't appear to be any significant differences in growth levels, trends, or temporal variability on any particular time scale. To see the differences more clearly a simple difference chronology for each data-type pair (with-PO minus without-PO) was computed (Figure 5C). The mean absolute deviation between these difference-chronologies is 0.035 for TRW, and 0.007 for MXD. Such low estimates of error are relatively small compared to the mean absolute deviations between the chronologies themselves (0.182 for TRW and 0.056 for MXD). We infer from this example that the impact of adding PO data to the RCS procedure is likely to be of minor importance. Maximum differences are 0.39 mm in A.D. 1132 and $-0.20$ mm in A.D. 1150 for TRW, and 0.048 g/cm$^3$ in A.D. 1146 and $-0.036$ g/cm$^3$ in A.D. 1133 for MXD. The largest differences between the paired chronologies often occurred in the early period when the sample depth is low. The early decades are also a time where there is a systematic, albeit inverse, relationship (positive for TRW and negative for MXD) in the PO difference-chronologies.

Adding PO data to the Gotland dataset, no doubt, leads to a more biologically correct RCS-chronology but the benefit, particularly in enhancing low-frequency information, is rather small. The influence of PO on RCS-chronologies is related to the distribution of POs through time (Figure 5A). If the POs are evenly distributed, their impact is small and not concentrated in any particular periods.

To investigate further the sensitivity of the RCS method to PO uncertainty we increased the PO values systematically by multiplying them two and four times, then re-calculated both the TRW RCS-chronologies (Figure 6A). Multiplication of the PO data increases the lengths and levels of the RC spline (Figure 6B). By artificially increasing the PO, the first values of the RC spline increase from below 2 mm (without PO) to more than 2.5 mm (with PO), and finally to more than 3 mm for PO×2 and PO×4. In addition, the mean curves of the age-aligned series show higher interannual variances in the early age-classes for PO×2 and PO×4. These dramatic changes result from unequal shifts caused by multiplying the PO data of the single series.

By comparison to the obvious impacts of artificially inflating PO on the RC splines (Figure 6b), the differences between the resulting four RCS-chronologies (Figure 6a) are relatively small. Major trends and variability do not differ all that much. Significant differences do appear in the early 1500s and in the very early period of the chronologies, particularly after multiplying the PO by a factor of 4 (Figure 6A). This is especially evident in the early 1500s, where a clear positive deviation develops. Some large POs, occurring around A.D. 1500, may be responsible for this noise but a conclusive explanation of this phenomenon needs further research (Figure 5A).

It is evident that the experimental PO multiplications dramatically modify the internal structure of the age-aligned data. The resulting RCS-chronologies are, nevertheless, robust for almost 900 years and significant changes occur only in particular periods after multiplying the PO by 2 and especially by 4. This conclusion is supported by the correlation coefficients between the chronologies that lie above 0.92 except for the without PO and PO×4 chronologies ($r = 0.84$) (Figure 6A).

## Influence of Sample Depth

Before venturing into the subject of sample depth and chronology quality, we state from the

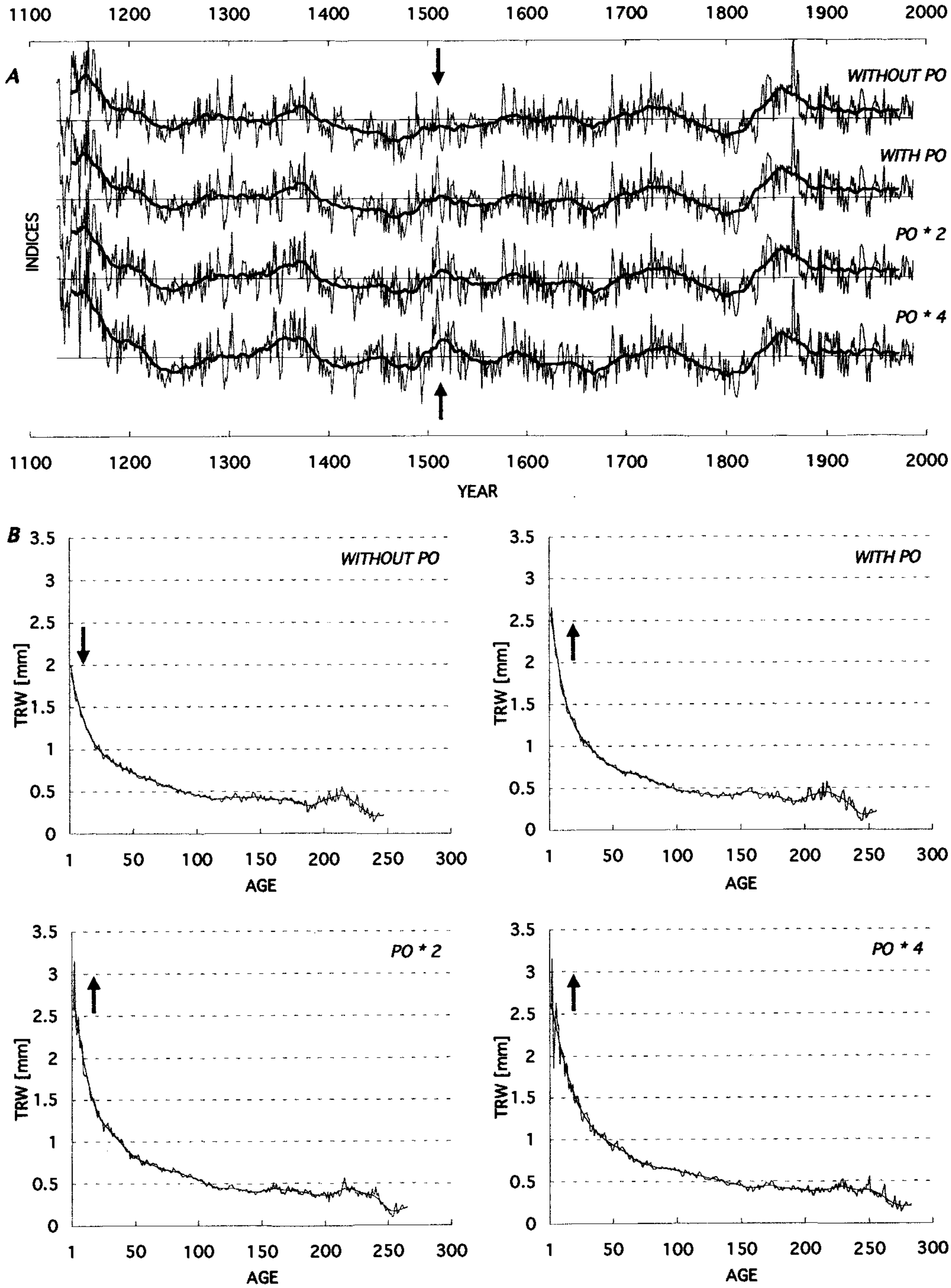

**Figure 6.** Gotland TRW RCS-chronologies after adding different pith offsets to the single series (A). (B) shows corresponding regional curve splines (smooth curves) and the mean curves of age-aligned series after adding different pith offsets. Arrows indicate a period when the chronologies are sensitive to pith offset in (A), and the direction ring width in the first years changes depending on the pith offset scheme in (B).

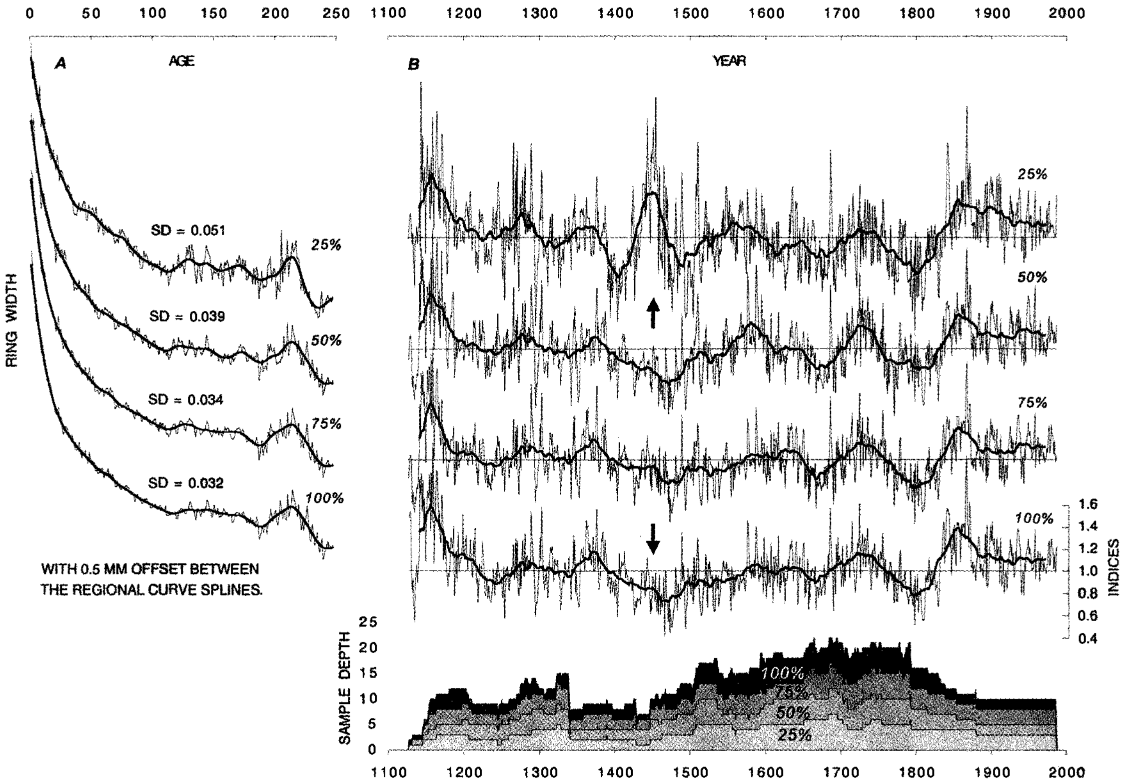

**Figure 7.** The effect of reduced sample depth (75%, 50%, 25%) on regional curve splines (A, smooth curves), and resulting RCS-chronologies (B).

beginning, "more is always better". However, as mentioned earlier on the subject of biological-growth populations, this does not mean that one could not improve a chronology by reducing the number of series used if the purpose of removing samples is to enhance a desired signal. The ability to pick and choose which samples to use is an advantage unique to dendroclimatology. That said, it begs the question, how low can we go?

By randomly removing series from the Gotland TRW dataset, we decreased the sample depths to 65 (~75%), 43 (50%) and 22 (~25%) series, then studied the effects on the resulting RC splines (Figure 7A) and RCS-chronologies (Figure 7B). For all three subsets, including the 100% set (86 series), differences in the RC level and slope, up to an age of ~100 years, are rather small. Low-frequency fluctuations of RC splines in age classes above 100 years are also similar until sample depth is reduced to 50%. However, decreasing sample depth does cause an increase in the variance of the mean age-aligned curves around the RC splines (Figure 7A). This is evident in the standard deviations of residuals of the mean curves from the RC splines. The standard deviations increase slightly from 0.032 to 0.034 and to 0.039 for 86, 65 and 43 series, respectively. When the sample depth is decreased to only 25%, the standard deviation jumps to 0.051. Even so, the age-aligned series in the 25% sub-set still produce a RC similar to those from 50%, 75% and 100% sets. So in this experiment, the RC is reasonably robust with respect to changing sample depth.

The most significant effect of reducing sample depth is not the relatively small differences between the RC splines but the noticeably larger differences in the resulting RCS-chronologies (Figure 7B). At 100% and 75% the two resulting RCS-chronologies are almost indistinguishable, indicating the RCS method can, in principle, tolerate relatively small sample depths, as few as 5–6, during some periods and still produce a relatively robust estimate of low-frequency signal. However, there is a clear limit to sample reduction as indicated in the RCS-chronologies based on the 50% and 25% sample depth cases. Fundamental differences, where the sample depth drops to 2 or 1 series are apparent (*e.g.* the mid 1400s, around A.D. 1560 and early 1700s). These findings suggest that at least 5 or more series in every period and more than 40 series in total are necessary to establish a stable RCS-chronology from material with the coherency and statistical properties of the Gotland data set (Figures 2 and 3).

## Influence of Species and Site

So far, the analyses of the RCS method have illustrated its reasonable robustness for a range of pith offsets and sample depths. Now we analyze the performance of RCS with a more complicated collection of data from two different species and two different sites. The two different species growing on the same site are represented by 119 *Pinus sylvatica* (PISYjae) series and 14 *Picea abies* (PCABjae) series from Jämtland, Sweden. From a different site, to the west, in Trøndelag, Norway we use 24 *Pinus sylvatica* series (PISYsk) (Bartholin and Karlén 1983; Bartholin 1984, 1990). The total number of individual series in this collection is 157. The three subsamples, reflecting different locations and species, also cover different periods over the last ~900 years (Figure 8A). PISYjae starts A.D. 1107 and extends, with a gap, to A.D. 1827; PCABjae starts A.D. 1423 and extends to A.D. 1827; PISYsk starts A.D. 1776 and extends to A.D. 1978. A 24-year gap within the PISYjae dataset, from (A.D. 1292–1315), was bridged with a single *Pinus sylvatica* series from northern Sweden (Torneträsk) to produce a continuous chronology from A.D. 1107–1978.

A striking feature of the Jämtland data is the significantly higher growth rates of the living PISYsk trees relative to all the others (Figures 8A and 8B). While both the PISYjae and PCABjae samples depict similar age-trends for TRW, the PISYsk mean TRW curve deviates up to 1 mm and takes a rather different slope. Interestingly, the age-aligned MXD mean curves fit closer together, indicating that RCS could be computed with all 157 series from all four collections.

The significant differences between TRW subsamples should bias the resulting RCS-chronology if left unattended (Figure 8C). Because the age-aligned mean curves indicate a homogenous collection of MXD series, the resulting MXD-RCS-chronology could be useful for climatic reconstructions. Conversely, TRW RCS-chronology shows an artificially shifted mean in the recent period since the early 1800s and relatively suppressed variation prior to that time. The variance in the two periods also differs significantly, indicating a failure of the RCS method. These problems are caused by the rapid-growing PISYsk samples forcing the RC spline too high for the older, slower growing samples. This feature, namely the significantly deviating growth rates and growth decreases with aging of the PISYsk samples, indicates the existence of a different population in the sense introduced earlier (Figure 8B). It also demonstrates the biasing effects of different populations and illustrates the fundamental requirement of the RCS method: sample homogeneity.

The gap A.D. 1292–1315 that was bridged with a 200-year-long series from Torneträsk is not filled successfully (Figure 8C). The MXD and TRW chronologies show remarkably opposing values during this period. This suggests that the Torneträsk data, used to bridge the gap, varies significantly from the Jämtland data.

## Influence of Multi-Site Samplings

Another collection investigated is a multi-site sampling from Switzerland containing many different small sites from the Lauenen region and additional sites scattered over the Swiss Alps (Schweingruber *et al.* 1987). These data sets integrate 206 series from *Picea abies* and *Abies alba* trees. To give an overview, we began by building three site-composite TRW, raw-average chronologies representing 114 *Picea abies* series from Lauenen (PCABlau), 71 *Picea abies* series from various locations (PCABvar), and 21 *Abies alba* series from various locations (ABLAvar) (Figure

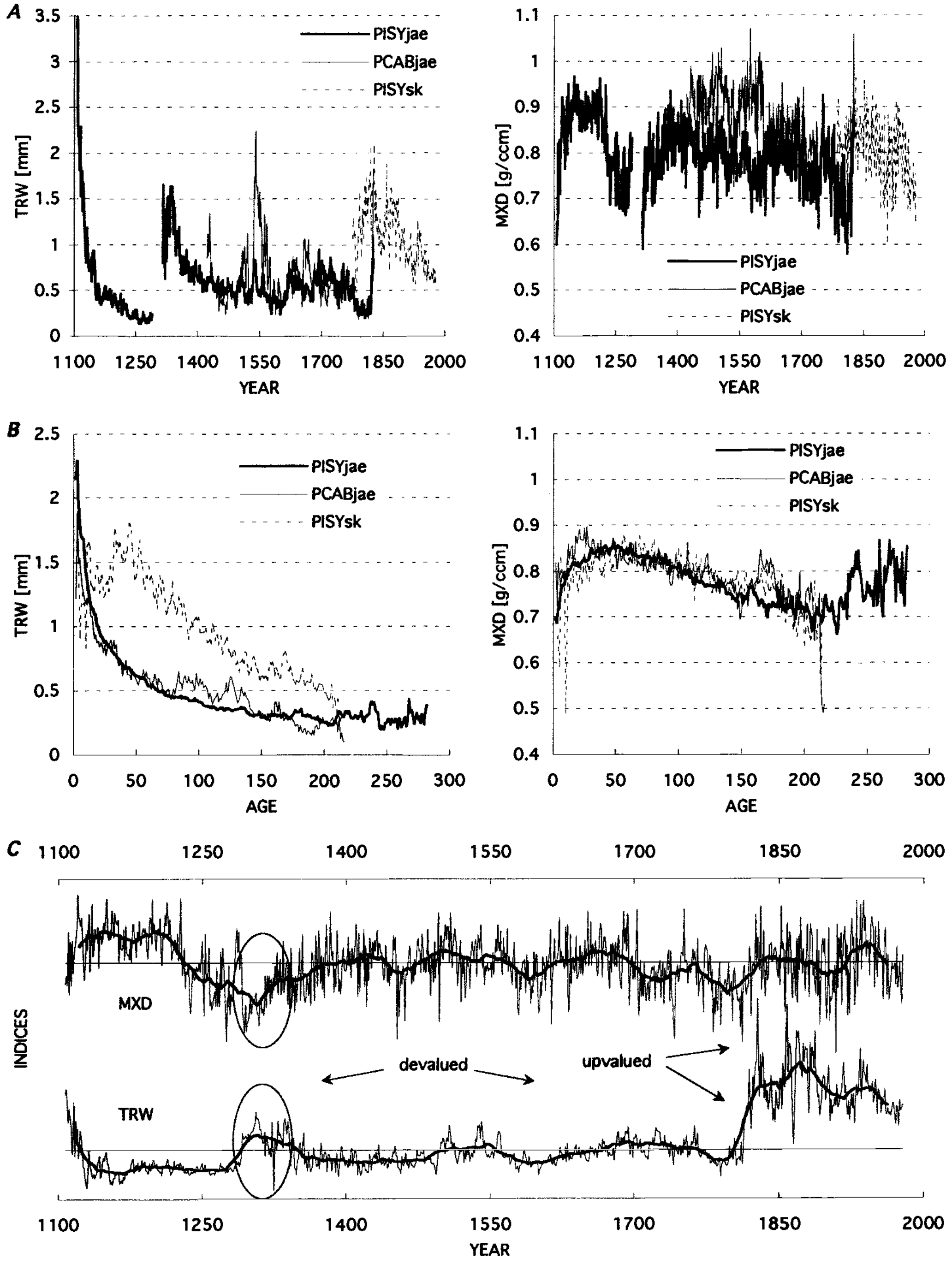

**Figure 8.** Raw TRW and MXD chronologies from different species (PISY = *Pinus sylvatica*, PCAB = *Picea abies*) and different sites (jae and sk) in Scandinavia (A). (B) shows the age-aligned mean curves of the sub-samples, and (C) the resulting RCS-chronologies.

9A). The data from these three composites cover distinctly different periods, are growing at different growth levels, from *ca.* 0.5 mm up to *ca.* 5.5 mm, and are segmented into several discontinuous periods (PCABvar and ABLAvar). The raw chronologies indicate a very heterogeneous tree-ring collection that would give any dendrochronologist reason to pause. Could such a collection be suitable for the RCS method?

To test these data for different populations we analyzed the TRW series in the manner used for the Gotland data. After alignment by cambial age, all sites' TRW data indicate remarkably similar age-trends (Figure 9B). Starting from the first year (cambial age = 1) the levels and slopes of the average curves are reasonably similar, suggesting all trees belong to the same population and that RCS could be applied. Single peaks and the increased variation in higher age classes (>100 years) are of minor importance. They result from a few older trees. The mean SL of the data is only 97 years.

Because the chosen classification of sites' TRW data is somewhat arbitrary (other partitions are possible) and because the age-aligned mean curves do not show variation between all the sites' TRW data, a scatter diagram of TRW versus SL for all series was made to further verify use of the RCS method (Figure 9C). The TRW-SL distributions of PCABlau, PCABvar, and ABLAvar all show a relationship between mean TRW and SL at least as good as that of the Gotland data (Figure 3C). The presence of a similar age-dependent, decreasing relationship between TRW and SL in the Swiss multi-site collection suggests the existence of one "biological-growth" population if the properties of the Gotland data are considered a fair reference. We believe this kind of analysis and comparison is valuable for determining whether the calculation

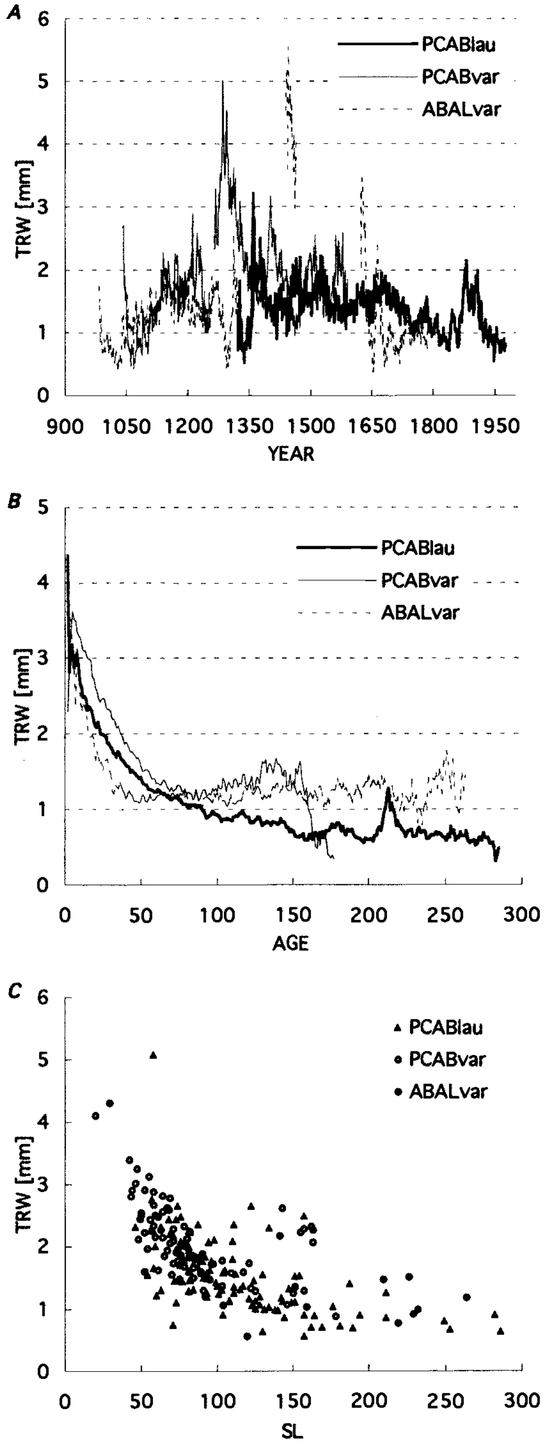

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**Figure 9.** Multi-site collection from the Swiss Alps, containing *Picea abies* from the Lauenen region (PCABlau), *Picea abies* from various sites (PCABvar), and *Abies alba* from various sites (ABLAvar). (A) shows the raw chronologies of the subsamples, (B) the age-aligned mean curves, and (C) the relationship between average TRW versus segment length for each series.

of one RC is useful, even if the data represent a multi-site collection.

## DISCUSSION

RCS is clearly sensitive to the effects of different subsample populations entering into the calculation of single RC. Including samples from different "biological-growth" populations in one RCS run could bias the resulting chronologies (*e.g.* TRW in Figure 8C) thus affecting interpretations of climate made from the resulting chronologies. However, opportunities to test the data for the existence of different populations are limited. This dilemma originates from the condition that RCS requires only one RC for *all* series then calculates anomalies from this one function for each single series. This approach works like a black box, making latent defects during the standardization process difficult to detect. Such defects can be studied and corrected much more easily when each single series is standardized individually. We recommend separating the data into possible subsamples then analyzing (i) the raw chronologies, (ii) the mean curves after age-alignment, and (iii) the relationship of the mean versus the age of individual series (*e.g.* Figures 3, 8, 9). The classification of population subsamples might follow the meta-information of a collection, and should certainly consider such differences as dead versus living trees, site ecology and species composition.

Analysis of millennium-length chronologies shows that the chosen calculation method (residuals, ratios, PT plus residuals) can have a significant effect on resulting RCS-chronologies. Differences caused by the use of different calculation methods often surpass the influence of other factors such as PO or sample depth. The selection of the most suitable calculation method is not trivial and we cannot recommend one. Tests with the Gotland data showed that residuals are a useful calculation technique, particularly if high-variance periods of young trees and low-variance periods of old trees are somewhat evenly distributed over the entire chronology length. Tests with other millennium-length data sets showed ratios can also produce a valid RCS-chronology, particularly if the RC splines do not significantly drop below 0.5 mm. We recommend trying ratios and residuals with every data set and perhaps comparing the results with chronologies obtained after power transforming the individual series.

In spite of the multiple-population problem and the calculation method issue, RCS is a reasonably robust method for preserving multi-centennial variations in long tree-ring chronologies. RCS can be applied to TRW, as well as to MXD data. Tests with and without PO data showed that missing PO information does not necessarily cause significant changes in the RCS-chronologies. However, this conclusion holds only for data sets with PO distributions similar to those investigated in this experiment. In datasets using sub-fossil remnants, where much of the center wood is missing, or it is unclear where on a stem the sample came, an accurate PO estimate will be difficult to make. The results from TRW and MXD data shown here also indicate that the influence of PO on RCS-chronologies is mostly independent of the slope of the RC near the pith. In such cases where the RC slope is weakly negative, the lack of PO information will not be serious.

Similar results were obtained when artificially varying the chronology sample depths. For data with properties similar to the Gotland collection the sample depth in any given period of a chronology should not fall below 5 series and the total number depending on SL, total chronology length, and other discussed parameters, should at least exceed 40 series.

The results obtained from tests with differing species and multiple sites indicate that, in principle, the RCS method can be used on large tree-ring collections from different regions if all series are from the same biological-growth population. Of course, this conclusion presupposes that the climatic signals in the collections are reasonably similar. If so, the RCS method has the potential to reconstruct low-frequency, centennial growth trends over larger regions, continents and even hemispheres. Assuming that climate (Jones *et al.* 1997) and tree-ring signals are more homogeneous over space in the low-frequency domain, the calculation of RCS with tree-ring data, even from different continents, might be a useful alternative (Esper *et al.* 2002) to averaging regional mean chronologies for use in hemispheric reconstructions (Crowley 2000; Crowley and Lowery 2000). If multi-site and multi-species samplings are jointly entered in one RCS run, comparisons of the age-aligned series and of mean TRW (or MXD) versus SL are necessary.

Further tests of the RCS method need to be carried out on more long chronologies. We recommend testing data sets at least for the existence of different biological-growth populations. When using RCS one has to decide whether differences between subsamples reflect (i) climatic signals and should be preserved or (ii) non-climatic signals and should be eliminated. If significant differences occur between various subsamples, some discussion on the impact these differences will have on the resulting chronologies would be useful. When the sample depth is small, care should be taken in interpreting the early periods of RCS chronologies. Tests with different POs and, where applicable, analyses of differences between species and sites can improve the resulting chronologies significantly. If all these factors are considered together, RCS can be a powerful tool for reconstructing multi-centennial climatic variability.

## ACKNOWLEDGMENTS

We thank the former editor of TRR Tom Swetnam, the current editor of TRR Steven Leavitt, and three anonymous reviewers for helpful comments on the manuscript. Tree-ring data provided by the Swiss Federal Research Institute WSL, Switzerland. Supported by the Max Kade Foundation, Inc., USA, and the Swiss National Science Foundation, Grant (2100–066628 (to J.E.). Lamont-Doherty Earth Observatory Contribution No. 6534.

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*Received 6 March 2001; accepted 21 July 2003.*