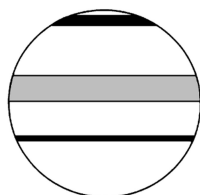


Mongolian tree-rings, temperature sensitivity and reconstructions of Northern Hemisphere temperature

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Abstract: Much of northern Asia is lacking in high-resolution palaeoclimatic data coverage. This vast region thus represents a sizeable gap in data sets used to reconstruct hemispheric-scale temperature trends for the past millennium. To improve coverage, we present a regional-scale composite of four tree-ring width records of Siberian pine and Siberian larch from temperature-sensitive alpine timber-line sites in Mongolia. The chronologies load closely in principal components analysis (PCA) with the first eigenvector accounting for over 53% of the variance from AD 1450 to 1998. The 20-year interval from 1974 to 1993 is the highest such growth period in this composite record, and 17 of the 20 highest growth years have occurred since 1946. Thus these trees, unlike those recently described at some northern sites, do not appear to have lost their temperature sensitivity, and suggest that recent decades have been some of the warmest in the past 500 years for this region. There are, however, comparable periods of inferred, local warmth for individual sites, e.g., in 1520–1580 and 1760–1790. The percent common variance between chronologies has increased through time and is highest (66.1%) in the present century. Although there are obvious differences among the individual chronologies, this result suggests a coherent signal which we consider to be related to temperature. The PCA scores show trends which strongly resemble those seen in recent temperature reconstructions for the Northern Hemisphere, very few of which included representation from Eurasia east of the Ural Mountains. The Mongolia series therefore provides independent corroboration for these reconstructions and their indications of unusual warming during the twentieth century.

Key words: Mongolia, tree-rings, temperature reconstructions, dendroclimatology, twentieth-century warming, Northern Hemisphere.

Introduction

Mongolia is a continental land area with forests restricted mainly to the northern third of the country, primarily on north-facing slopes. At locations in the western mountains far removed from towns, there is little disturbance due to human activity and excellent opportunities for dendroclimatic study of old-growth trees in alpine timber-line settings (i.e., at the elevational limits of survival) (Figure 1). Since 1995, members of MATRIP (the Mongolian-American Tree-Ring Project) have been collecting wood samples from climatically sensitive locations in Mongolia for dendroclimatic studies of both temperature (Jacoby *et al.*, 1996) and precipitation (Pederson *et al.*, 2000).

Alpine timber-line sites can complement high-latitude tree-line locations for analyses of past temperature. A 450-year ring-width chronology (Solongotyin Davaa, formerly called Tar Pass) was produced from Siberian pine (*Pinus sibirica* Du Tour) at timber-line (2450 m) in Mongolia's Tarvagatay Mountains (Jacoby *et al.*, 1996). This record shows low-frequency growth variations which closely reflect those seen in Arctic and Northern Hemisphere temperature reconstructions, all of which indicate unusual warming in the twentieth century relative to the prior period (Jacoby and D'Arrigo, 1989; Bradley and Jones, 1993; D'Arrigo and Jacoby, 1993; Overpeck *et al.*, 1997; D'Arrigo *et al.*, 1999; Mann *et al.*, 1999). Almost none of these reconstructions, however, included coverage over the immense land mass of north Asia east of the

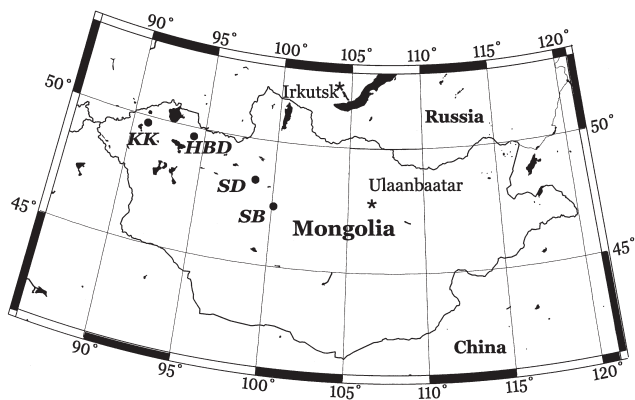


Figure 1 Map of Mongolia showing locations of alpine timber-line sites and other locations mentioned in text. KK = Siberian larch; HBD = Siberian larch; SD = Siberian pine; SB = Siberian larch.

Ural Mountains. In this paper, we better replicate and confirm initial findings (Jacoby *et al.*, 1996) by presenting a regional-scale composite of four chronologies produced from elevational tree-line forests in northwestern Mongolia.

One of the chronologies (Khalzan Khamar, KK) is from a site in the Altai Mountains; two (Horin Bugatyin Davaa, HBD, and Suuleen Bagtraa, SB) are in the Hangai Mountains; and one (Solongotyin Davaa, SD), is in the Tarvagatay Mountains, a north-eastern extension from the Hangai (Figures 1 and 2). The higher elevations have permanent or semi-permanent snowfields, ice and/or permafrost. The trees, of Siberian pine and larch (*Larix sibirica* Lebedour), were sampled at or very near timber-line (exceeding 2200 m elevation) in settings where temperature, rather than drought stress, appears to be the limiting factor to growth. We base this interpretation on the presence of lush ground vegetation, water seepage, correlations with climate, and other considerations (Jacoby *et al.*, 1996).

Methods and results

Samples were dated and processed using basic dendrochronological techniques (Fritts, 1976; Holmes, 1983; Cook and Kairiukstis, 1990). Final chronologies were generated using conservative curve-fitting methods in the standardization process (Cook and Kairiukstis, 1990). Although there were older individual trees sampled at each site, the common period was truncated to AD

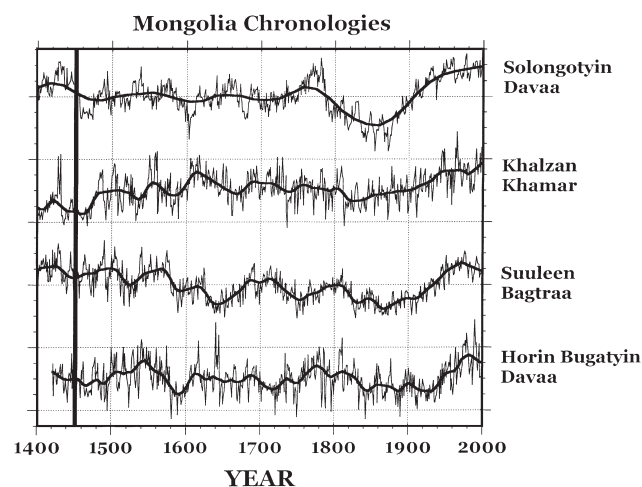


Figure 2 Time-series of four ring-width chronologies (indices) for 1450–1998. Vertical line is indicated at AD 1450 where common period of analysis begins. Their full lengths of record (not shown) are: KK 1326–1998; HBD 1422–1998; SD 262–1998; and SB 1363–1999.

1450–1998. Statistical evaluations indicate coherent variation among the samples for each site (Cook and Kairiukstis, 1990). One criterion used to evaluate the chronologies is the expressed population signal, or eps. The eps is an absolute measure of chronology error that determines how well a chronology, based on a finite number of trees, approximates the theoretical population chronology from which it has been drawn. While there is no significance level *per se*, a value of 0.85 is considered acceptable by some researchers (Wigley *et al.*, 1984; Cook and Kairiukstis, 1990). The mean eps values for the Mongolia series for 1450–1998 are: KK 0.96; HBD 0.88; SD 0.96; and SB 0.96. Series intercorrelation coefficients also indicate agreement between cores at each site (Holmes, 1983). For the four series these are 0.74, 0.72, 0.62 and 0.74.

The first eigenvector in principal components analysis (PCA) accounts for over 53% of the overall variance and shows closely similar loadings among the series: KK 0.481; HBD 0.503; SD 0.520; and SB 0.496. The percent common variance between chronologies has increased since AD 1600 and is highest (66.1%) for the twentieth century. Although there are obvious differences among the individual chronologies (Figure 2), these results indicate a coherent signal which we consider to be related to temperature.

The nearest and longest individual station record is at Irkutsk, Russia, just north of the Mongolian border; this station shows a significant positive trend over the past 100 years ($r=0.66$). Irkutsk is hundreds of kilometres from the tree-ring sites and at much lower elevation (470 m, Figure 1). Despite these considerations, annually averaged (August to July) Irkutsk temperatures and gridded temperatures for Mongolia based largely on the Irkutsk station (45–50°N, 95–100°E, P. Jones) had shown significant positive correlation with the original Sol Dav series (e.g., from 1882 to 1993, $r=0.45$ with the gridded data for the growth year; Jacoby *et al.*, 1996). Correlation for the four-chronology PCA scores is $r=0.57$ with Irkutsk temperatures over 1883–1996.

Comparison with large-scale temperature reconstructions

We compare the PCA scores to two annual Northern Hemisphere temperature reconstructions: a new reconstruction based solely on tree-rings and another based on various proxy and other data sources (Mann *et al.*, 1999) (Figure 3). The former is based on tree-ring data from 21 mesic to hydric sites at either latitudinal or elevational tree-line in northern latitudes (modified from Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993; D'Arrigo *et al.*, 1999). This particular set of sites was selected for balanced geographic representation, and accounts for 66% of the variance in recorded annual temperatures. Tree-ring data for years t and $t+1$ were used in a principal component regression to estimate temperature for year t .

Correlations with the Mongolia series and these reconstructions are 0.67 (with tree-ring reconstruction) and 0.47 (with Mann reconstruction) over AD 1655–1973 and 1450–1980, respectively. The four chronologies also load closely with the 21 tree-ring chronologies used in the reconstruction above, which included data from North America, Scandinavia and Russia, as well as one Mongolian series. This agreement between such widely separated sites further suggests a common climatic signature.

Trends seen in the Mongolia PCA record track those indicated in the above large-scale reconstructions, with higher growth indicating warmer temperatures and lower growth cooler conditions. Common trends include pronounced cooling in the early to middle 1800s during the last phase of the 'Little Ice Age' (Grove, 1988) and a subsequent warming trend for this century (Figure 3). Similar fluctuations have been noted in other long-term records of

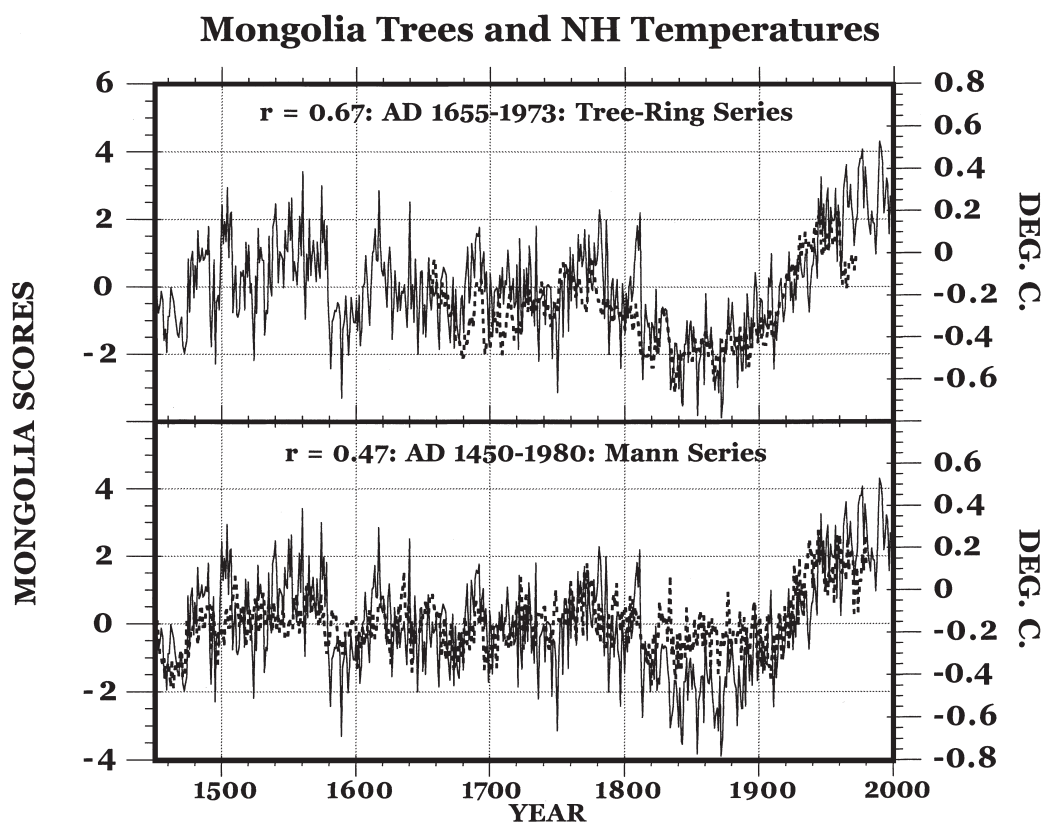


Figure 3 Comparison of Mongolia PCA scores from 1450–1998 (solid lines) with Northern Hemisphere annual temperature reconstructions (dashed lines). Above: based solely on tree-ring data (modified from Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993; D'Arrigo *et al.*, 1999). Below: based on various proxy and other data sources (Mann *et al.*, 1999).

temperature for north Asia (e.g., Zang, 1980). The 20-year interval from 1974 to 1993 is the highest such period over the length of record. Furthermore, 17 of the 20 highest growth years have occurred in the twentieth century (since 1946). There are, however, some comparable periods of inferred warmth for some of the sites during other intervals (e.g., 1520–1580 at SB and HBD; and 1760–1790 at SD and HBD) (Figure 2). The lowest 20-year period occurs from 1854 to 1873, just prior to the recent warming.

The new data provide independent evidence for the trends seen in the large-scale temperature estimates, which included no or very limited data coverage from north central Asia. In particular, these new data provide independent support for the interpretation that recent warming is unusual in nature (Briffa and Osborn, 1999). The twentieth-century rise in common variance between series could suggest a common climatic forcing which is increasing relative to regional differences.

As noted, we interpret the climatic signal at the tree-line sites in Mongolia to be primarily due to temperature. Apparent loss of temperature sensitivity in some northern tree-ring series has been observed in recent decades, attributed to drought stress and other factors (Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998; Vaganov *et al.*, 1999). Yet such decreased sensitivity is not clearly evident in these tree-line data from Mongolia. Careful site selection is critical for identification of those trees and locations where the response to temperature has not been diminished.

Conclusions

Additional palaeorecords are essential for evaluation of climatic change, including detection of possible recent anthropogenic influences. One key challenge is to decrease the large degree of error found for the earlier half of this millennium in existing hemi-

spheric-scale temperature reconstructions (Mann *et al.*, 1999). Relict wood material are now being used to extend the living tree records back to the millennial scale for Mongolia and these other locations. Besides the Mongolia series, other primarily temperature-related tree-ring chronologies for northern Eurasia have recently been developed for the Taymir Peninsula, Russia (Jacoby *et al.*, 2000) and elsewhere in Siberia (Briffa *et al.*, 1995; Hughes *et al.*, 1999, Vaganov *et al.*, 1999). These and other such records will prove useful in future generations of temperature reconstructions, but much more data is needed (Briffa and Osborn, 1999). The new data will contribute significantly to existing geographical coverage while helping to decrease the level of uncertainty inherent in present large-scale reconstructions of climate variability.

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