

# Long-Term Temperature Trends and Tree Growth in the Taymir Region of Northern Siberia

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Received July 28, 1999

**The northernmost conifers in the world are located well above the Arctic Circle in the Taymir region of northern Siberia and have been recording the thermal environment for centuries to millennia. The trees respond to temperatures beyond the narrow season of actual cambial cell division by means of root growth, photosynthesis, lignification of cell walls, and other biochemical processes. Data from annual tree-ring widths are used to reconstruct May–September mean temperatures for the past four centuries. These warm-season temperatures correlate with annual temperatures and indicate unusual warming in the 20th century. However, there is a loss of thermal response in ring widths since about 1970. Previously the warmer temperatures induced wider rings. Most major warming and cooling trends are in agreement with other high-latitude temperature reconstructions based on tree-ring analyses with some regional differences in timing of cooling in the late 18th century and of warming in the late 19th century.**

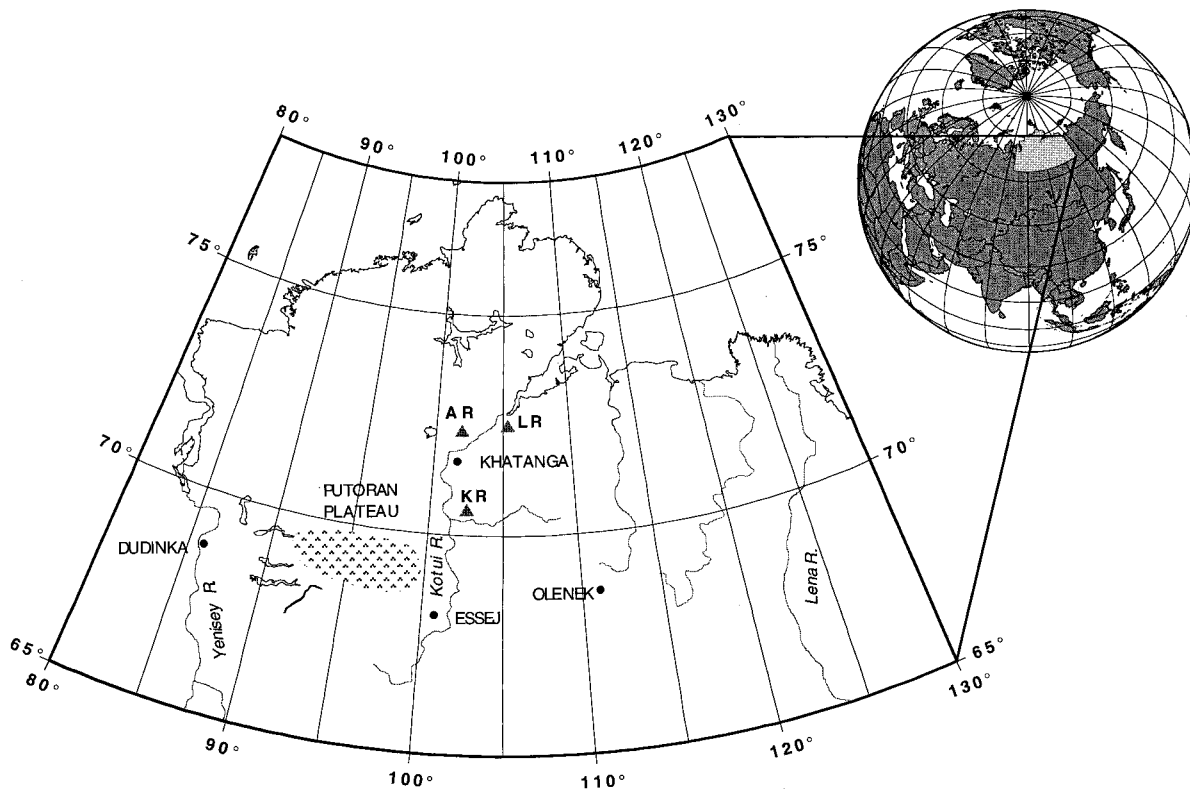
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**Key Words:** tree rings; temperature; Arctic; paleoclimate; Siberia.

## INTRODUCTION

The northernmost erect conifers in the world, growing in the Taymir region of northern Siberia poleward of 72° N latitude

(Fig. 1), are living monitors of the surrounding arctic climatic environment. At selected sites the trees record the thermal environment by the widths of their annual rings, generally forming a wider ring in warm years and a more narrow ring in cold years. The series of ring widths of old-aged *Larix gmelini* (Dahurian larch) can be used to reconstruct a history of temperature variations over the past four centuries or more. Some recent studies have demonstrated the paleoclimatic value of larch sampled in the Taymir region (e.g., Vaganov *et al.*, 1996; Panyushkina *et al.*, 1996) in relation to summer temperatures. We find similar results, but in our analyses we consider the trees' response over a longer season than just summer months. The longer season response indicates a long-term pattern similar to tree-temperature trends from other Northern Hemisphere dendroclimatic studies (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992). A shift occurs in the tree response to temperature about 1970, similar to changes in Alaska and Canada (Jacoby and D'Arrigo, 1995). Tree growth, as evidenced by ring widths, is less than expected. Several hypotheses exist for the causes for this reduced growth (Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998; Vaganov *et al.*, 1999), but the question is not resolved at this time and is beyond the scope



**FIG. 1.** Map of the Taymir study region in northern Siberia, Russia. The inset on the globe locates the Taymir region. Triangles are tree-ring sampling sites: AR, two sites at Ari Mas and Ari Mas South; LR, Lukunskaja River; KR, Kotuikan River. Solid circles are meteorological stations with 50 years or more of recorded temperature data.

of this paper. These trees provide reliable records of the thermal environment prior to 1970 and indicate unusual warming in the 20th century.

### METEOROLOGICAL DATA

Inclusion of more than one station in a time series of meteorological variations tends to reduce the noise that may be present in a single station record (Blasing *et al.*, 1981). Several meteorological stations in the Taymir region (Fig. 1) have occasional missing values, and data indicate a possible station shift in at least one record. Therefore, it is best to merge stations rather than rely upon the record from a single site.

Monthly mean temperatures from four stations were used in this study (Table 1). All monthly data for each station were plotted and compared. The 1956 Khatanga temperature record seemed to disagree with the other stations in the region. The months that differed were changed using values estimated by regression with the Dudinka station. Starting in 1966, the Olenek record has an anomalous shift to higher values for the winter months. Therefore, this station was dropped from 1966 to the end of the record.

The four-station regional temperature record was developed by estimating missing values and averaging over the four stations. The missing values were calculated by using the

nearest station with the highest individual monthly correlations with the station to be estimated. Correlations of monthly temperature data between stations ranged from 0.65 to 0.94, and between Dudinka and Khatanga they were 0.68 to 0.87. The resulting series of monthly temperatures for 1933 to 1990 represents regional temperature variations and was used in the initial correlation and model analyses with the tree-ring data.

A two-station record also was made using only data from the Dudinka and Khatanga sites. These two stations have slightly longer records and are located in the lowlands that are closer to, and more exposed to, the effects of the Arctic Ocean air masses than are the Essej and Olenek stations, which are

**TABLE 1**  
**Meteorological Stations**

Station name	N latitude	E longitude	Record length <sup>a</sup>
Dudinka	69°40'	86°17'	1906–1990(1933)
Essej	68°47'	102°37'	1937–1990
Khatanga	71°98'	102°47'	1929–1990(1933)
Olenek	68°50'	112°43'	1935–1990

<sup>a</sup> Years in parenthesis indicate the start of a continuous record with few gaps or missing years.

located in the interior plateau (Fig. 1). Three of the tree-ring sites are in the lowlands.

The total monthly precipitation data were processed similarly to develop a regional series. Different stations were used because the most complete precipitation data were from stations other than those supplying the most complete temperature data. Although the thermal regime of air and soil temperatures influence growth (see below), the only regional time series available are air temperatures and precipitation.

### TREE-RING DATA

Trees were sampled by taking increment cores at four sites (Fig. 1; Table 2). All trees were *Larix gmelini*. Samples had been taken previously in the region by other researchers (Shiyatov *et al.*, 1996; Vaganov *et al.*, 1996; Panyushkina *et al.*, 1996). Our sampling covered similar locales. We subdivided one area by designating one set of cores as Ari Mas and the other set as Ari Mas South. The former was level terrain with no local slopes greater than about 5°, and the latter site was on a south-facing, gentle-slope area. Both sites have an open canopy, with little evidence of fire or human disturbance, except for one tree at Ari Mas. This tree was considered by a local forester to be the oldest *Larix* in the area, and it had previously been cored so many times that it probably was damaged. We did not find evidence of previous coring in any other of the trees sampled.

Trees were also cored near the Lukunskaja River. The locality has a 5°–15° slope to the south toward a lake. A few trees from level ground above the site were included in the sampling. The stand was open, with many well-preserved, relict trunks lying on the ground, indicating absence of fire for centuries. We collected seven sections from the relict trunks within the living-tree sampling area and 31 samples from relict trees up to 2 km north of the main area of living trees. Judging by size, location, and relict stump indications, all relict trees sampled appeared to be at the original location of the trees' falling. Combining the living and relict trees at this site produced a ring-width chronology extending back to A.D. 1170.

The Kotuikan River site is an alluvial terrace near the confluence with the Kotui River. The south side of the terrace faces the Kotuikan River. Permafrost melting and river erosion is exposing *in situ* subfossil stumps and tree trunks that were buried by alluvium. We took cores from the living trees and cut sections from the buried trees. Radiocarbon dating indicates that the floating chronology from the subfossil trees spans approximately 100 B.C. to A.D. 550. The living trees are in a level, closed stand, which lacks a dense canopy and shows little sign of disturbance, except for some small gullies from permafrost melting. No trees within 5 m of the eroded south side of the terrace were included in the sampling. Only living trees were used, because there is a time gap between the oldest living trees and the subfossil trees.

Depth to permafrost, measured in the summers of 1996, 1998, and 1999, varies within each site from 0.2 to 0.8 m,

**TABLE 2**  
**Site and Chronology Summary**

Site	N latitude	E longitude	Interval	Radii/trees
Ari Mas	72° 27.80'	101° 53.50'	1553–1995	51/16
Ari Mas South	72° 27.35'	101° 53.50'	1557–1995	43/13
Lukunskaja River	72° 30.04'	105° 09.46'	1170–1997	45/23
Kotuikan River	70° 37.24'	103° 27.46'	1420–1997	29/14

depending on microsite conditions and measuring points. Tree growth responds to the annual cycle of melting of the active layer, and to soil and air temperatures warming enough for root growth, photosynthesis, and other biochemical processes that ensue from spring through the lignification of cell walls at the end of the bioactive season (Tranquillini, 1979; Kramer and Kozłowski, 1979). The season of cambial-cell division is only about 4–6 weeks at high-latitude treeline (Giddings, 1941; Fowells, 1965). Temperature data for shorter periods can give significant correlations with ring-width data (e.g., Hughes *et al.*, 1999), but the correlations with monthly temperatures here and in other studies (e.g., Jacoby and D'Arrigo, 1989) indicate significant tree-growth/ring-width response over longer periods.

The samples were cross-dated and ring widths were measured using standard dendrochronological techniques (Cook and Kariukstis, 1990). The dating was checked using the quality control program COFECHA (Holmes, 1983). There were a significant number of missing rings (892 out of 45,824 rings, 1.9%), and dating presented some difficulties. Standardization to produce chronologies of ring-width indices was done using the ARSTAN procedure (Cook, 1985). Single detrending was done using curve fits of straight lines with horizontal or negative slopes or negative exponential curve fits. In less than 10% of the cases, a 200-yr spline was used. This conservative standardization keeps most of the climate-related variance in the ring widths and removes age trends. Three chronologies were produced by the version of the ARSTAN program used, a standard chronology, a residual chronology containing only the high-frequency variations, and an ARS chronology composed of the residual chronology with the communal modeled autoregressive variation added back into it (Cook, 1985).

### ANALYSES OF TREE-RING AND METEOROLOGICAL DATA

Each tree-ring chronology was compared to three sets of meteorological data. One set was from the Khatanga station only, a second set was from the combined average of Khatanga and Dudinka, and the third set averaged the four stations of Dudinka, Essej, Khatanga, and Olenek. The time interval tested was 1937 through 1970 (see below). The individual correlations with monthly temperature data for the year of growth vary from temperature data set to data set. The Dudinka–Khatanga record showed the highest positive correlations in 25

cases out of 43, but 5 negative correlations also occurred. Correlations with the four-station average were highest in 10 cases and in 7 cases with the Khatanga monthly temperatures. There was one tie between Khatanga and Dudinka–Khatanga. These results support merging data from the meteorological stations to produce a better record than is possible with single station data. Based on these results and the station locations (see above), a reconstruction using the Dudinka–Khatanga record was developed.

All four chronologies were used in the reconstruction. They were retested using the longer 1933–1970 Dudinka–Khatanga record. The results indicated that the addition of 1933 actually lowered many of the correlations between monthly temperature data and the tree-ring chronologies. Perhaps the temperature data from the first year of recording lack the quality of those from later years. Therefore, only the 1934 through 1970 temperature data were used in the reconstruction. A principal component regression analysis (Cook and Kariukstis, 1990) reduced the number of predictors in the estimation of temperatures. The analysis and reconstruction end at 1580 because only two trees from each of the Ari Mas and Ari Mas South sites extend past this year (Table 2).

## DENDROCLIMATIC ANALYSES AND RESULTS

All three chronologies (standard, residual, and ARS) from each site were compared to the monthly regional temperature and precipitation data. The results with the standard and ARS chronologies were similar, and the residual gave lower correlations. The standard chronology was used in further analyses, as it had slightly higher correlation with climatic variables than the ARS chronology. The ARS chronology is appropriate where competition is more of a growth factor than in these stands. Initial statistical and graphical comparisons indicate that the relationships between the tree-ring chronologies and the meteorological data changed about 1970 (Fig. 3). Models for temperature reconstructions were poorer if they included data from 1971 to 1989, the end of the meteorological data obtained for the region. We therefore decided to test the data as described above and make reconstructions using only the concurrent period of meteorological and tree-ring data from 1934 through 1970. A departure from stable and significant correlations between temperatures and tree-ring widths at high-latitude treeline sites near 1970 was noted previously (Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998). In north-central Alaska, the cause appeared to involve increased moisture stress, in part related to recent higher temperatures. However, in the Briffa *et al.* (1998) paper and in our own observations in Taymir, the cause may be more complex and not understood at this time, although Vaganov *et al.* (1999) hypothesize that it is due to the influence of snowfall and melt timing. Change in moisture stress may explain much of the problem in central Alaska but is not adequate to explain results universally.

The Lukunskaja River chronology had the highest individual explanation of variance ( $R_a^2$ ) due to monthly temperature from

1934–1970,  $R_a^2 = 0.36$  ( $p < 0.01$ ), and correlated positively with May–November temperatures (Fig. 2). Here,  $R_a^2$  is the variance explained after adjustment for loss of degrees of freedom due to the regression. If the temperature data from 1971–1989 are included, the  $R_a^2$  drops to 0.21. Moisture stress is almost absent from 1934–1970, showing only significant correlation with August precipitation. However, for the period 1970–1988, July–October monthly precipitation during the prior year can explain 44% of the variance in the chronology.

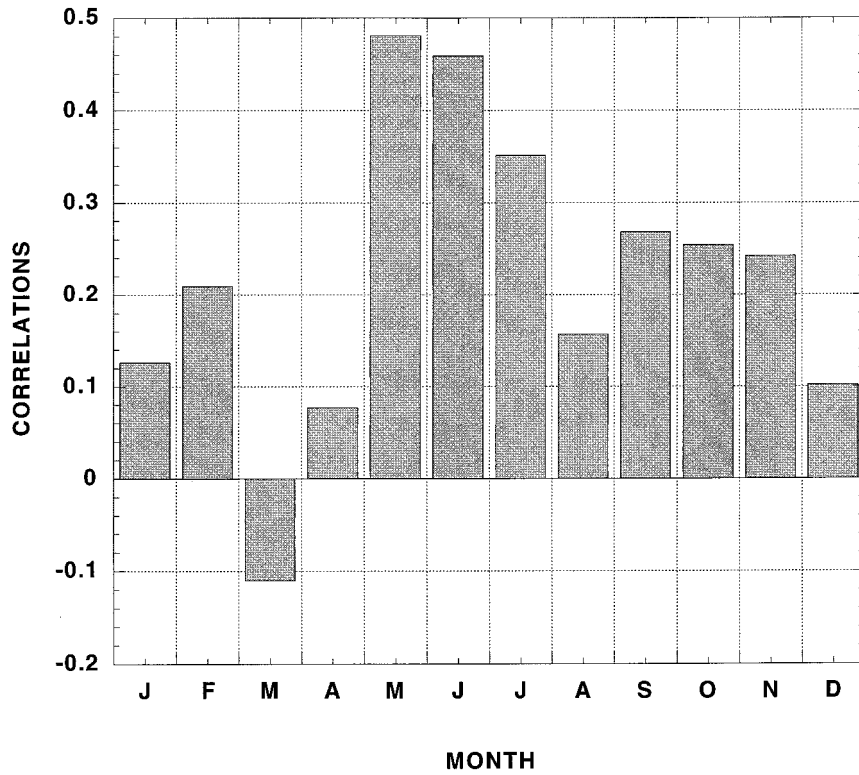
Principal component analysis (PCA) was used to develop a reconstruction of warm season temperature for the Taymir region based on the four chronologies. The mean temperature for May through September was reconstructed because the combined chronologies correlated best with that season. A reconstruction of mean May through September temperature, extending back to 1580, explains 46.3% of the variance in temperature (Fig. 4). Variance explains drops to 43.4% if 1933 is included. The reconstruction does not use any leads or lags, and only the first principal component, which contains 81% of the variance of the four chronologies, is used as a predictor. Thus, the reconstruction is merely the first eigenvector rescaled into degrees Celsius. A decreased response of the trees to temperature starts in about 1970 (Fig. 3).

The data set is too short for meaningful division into two sets for the calibration and verification that is typically done in dendroclimatic reconstructions (Cook and Kariukstis, 1990). However, temperature data exist for the warm season from 1907 through 1923 from Dudinka. The same PC regression using the four chronologies explains 31% of the May through September temperature over this interval. This result helps confirm the temperature signal in the trees. However, it is weaker, likely due to having only single station temperature data and to Dudinka not being as central to the region of sampling as Khatanga (Fig. 1).

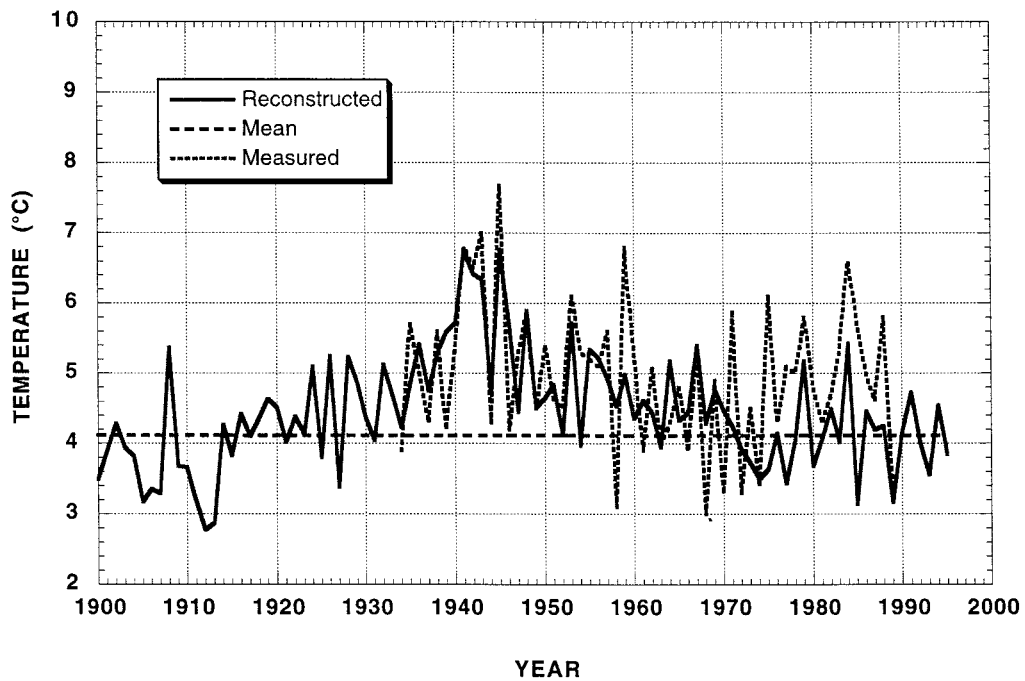
## DISCUSSION

This temperature reconstruction for the Taymir region shows an unusual warming during the first half of the 20th century (Fig. 4). This warming was not apparent in the reconstruction of summer temperatures for the same region by Vaganov *et al.* (1996), but they correctly stated that such low-frequency trends may have been removed by their standardization and prewhitening procedures. Recorded temperatures and ring widths declined after about 1950 but stayed well above the long-term mean. Recorded temperature increased again after about 1970, but the trees failed to respond accordingly.

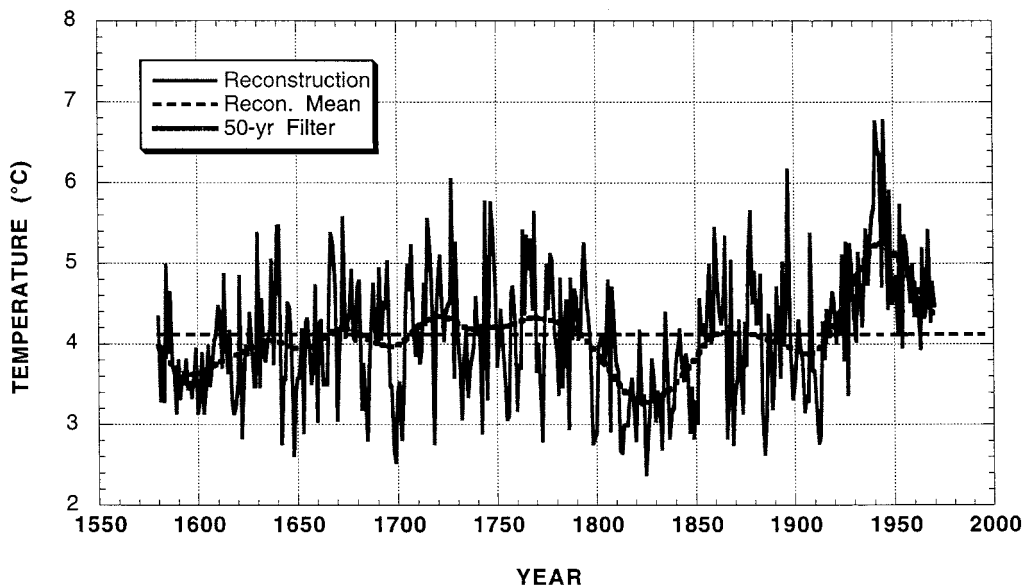
The Taymir reconstruction shows some of the same trends as do reconstructions for the Arctic (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992; G. C. Jacoby, unpublished data). The correlation between recorded May–September temperature and annual temperature is 0.68. Thus, the reconstruction bears some relationship to annual temperature. The Taymir reconstruction was smoothed with a 50-yr filter and plotted with a reconstruction of annual



**FIG. 2.** Correlations between monthly regional temperature and the Lukunska River tree-ring chronology, 1934–1970. Significant correlations extend from May through November, with the exception of August.



**FIG. 3.** Comparison between estimated and recorded temperatures since 1900. Both data series indicate warming and the subsequent decline to 1970. Recorded temperatures have subsequently recovered to levels of the 1930–1960 period. However, the trees show obvious reduced response to temperature after about 1970. Calibration and reconstruction are truncated in 1970 (see text).

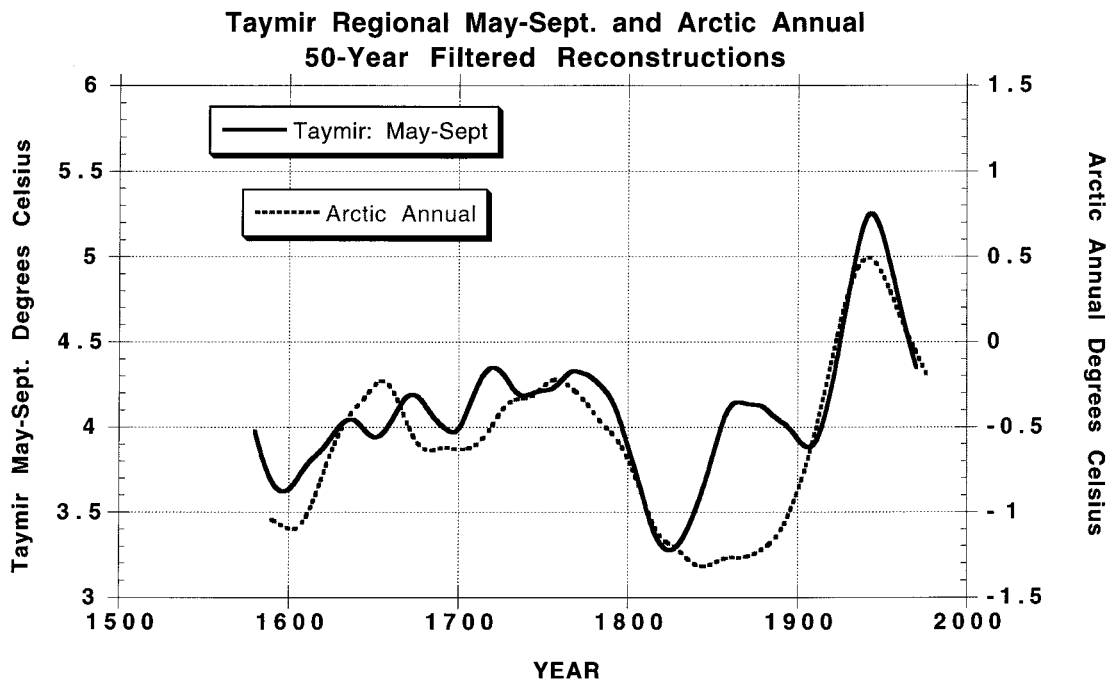


**FIG. 4.** Reconstruction of May through September mean temperature based on four tree-ring-width chronologies, Ari Mas, Ari Mas South, Lukunskaja River, and Kotuikan River. The plot shows an unusual increase in temperature during the first half of the 20th century. Also, note the cold period during the early 1800s. Many trees died at this time and are preserved as relict trees due to the slow decay in this cold region.

arctic temperatures (Fig. 5). The major regional difference is a warmer second half of the 19th century. This feature appears in reconstructions using Eurasian data (Bradley and Jones, 1992; Hughes *et al.*, 1999) but less so in reconstructions based largely on North American data (D'Arrigo and Jacoby, 1992). However, a temperature-sensitive tree-ring

series from Mongolia (Jacoby *et al.*, 1996) does not show the late 19th-century warm interval. Thus, despite substantial regional differences, agreement exists for the 20th-century warming and some earlier trends.

The recent warming trend is a real feature in the ring widths. The wider rings can be seen in most core samples as they are



**FIG. 5.** Comparison between the Taymir reconstruction and arctic annual temperatures, as reconstructed using latitudinal treeline sites and high elevation treeline sites from northern regions. The absolute scales are different, but the magnitude of change and the trends are similar, except for in the late 1800s.

removed from the trees, providing a visual communal signal of improved growth conditions in this century. Wider rings also appear in the 18th century. The conservative standardization process removes primarily age-related growth trends and preserves the low-frequency trends visible in the cores themselves.

### CONCLUSIONS

The *Larix* growing at latitudinal treeline in the Taymir region of Siberia are temperature stressed and record the effects of varying warm-season temperature in their ring-width variations. The same species of trees, located more than 200 km inland, also can have a similar response to temperature. The seasonal response extends beyond the season of actual cambial cell division. If the common low-frequency variation in data processing and climatic modeling is preserved, the warming of the 20th century is clearly shown in temperature reconstructions through 1970. With some regional differences, the long-term trends of temperature in Taymir are similar to larger-scale Arctic and Northern Hemisphere trends.

### ACKNOWLEDGMENTS

This research was supported by grant ATM 98-09230 from the Climate Dynamics Program, National Science Foundation, with additional support from the International Division, by grant ENVIR.LG.972753 from the North Atlantic Treaty Organization, and by the Climate Center of the Lamont-Doherty Earth Observatory (LDEO). D. Bunker and R. Free aided in analyses, and Y. Begin gave helpful comments. This is LDEO contribution 6031.

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