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The influence of climatic factors on radial growth of timberline trees in the Urals

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Introduction

The aim of this investigation was to analyze the influence of climate on the annual growth of trees in the geographically unique Ural mountain area using multivariate techniques. These techniques have not been used in the Soviet Union over large regions such as this one, although results have been reported concerning the climate caused growth, cycles and dating.

During 1960-1975 the first author sampled cores and developed more than 30 chronologies from coniferous trees growing at the upper timberline in different natural provinces in the Urals. Within the Polar Subpolar and North Urals, one characteristic site was selected for each natural province. Within the South Urals two characteristic sites were selected.

The Urals high mountain profile is 1600 km long including the Polar, Subpolar, North and South Urals. An analysis of the climatic influence on growth of trees at their upper limits along this profile is of great interest because the upper timberline in different natural provinces in the Urals is formed by the same coniferous species - *Larix sibirica* and *Picea obovata*. In addition, the forest vegetation of mentioned sites is slightly disturbed by intensive farming. By using the same sampling, measuring and standardization procedures for all sites we hoped to be able to evaluate changes along this gradient.

Data

Thirty tree-ring chronologies, along with both Grid Point Temperature estimates (Jones et al. 1985) and the temperature and precipitation data from proximate meteorological stations, were used in this evaluation. However the Grid Point Temperature data were longer records, so the interval of overlap with the tree-ring data that was used for calibration was longer than in the case of the station data. Most of the individual station data began in the 1930s. The Salehard meteorological station data (monthly mean air temperature and monthly precipitation totals) were used for the Polar and Subpolar Ural response functions described in this paper. Monthly climatic data from Taganai and Zlatoust were used to estimate the response functions for the South Ural sites.

Procedures

To estimate as closely as possible what climatic variables are statistically linked with growth, two different response-function programs were applied. The first computer program was developed at the Laboratory of Tree-Ring Research (TRL), University of Arizona, USA (Fritts 1976). Another program was written at the Climatic Research Unit (UEA), University of East Anglia, UK. The primary difference between the programs lies in whether prior-growth values are included in the calculation of the eigenvectors or whether prior-growth values are used as separate predictor variables of growth along with the PCs in a regression analysis (Fritts, Wu 1986). Thus in the TRL version, prior growth is entered on the basis of its correlation with the residuals in the regression, while in the UEA version it is already a part of the PCs, which are entered into regression. Another difference between the programs is that TRL program uses a stepwise regression while the UEA version uses standard multiple regression. Never the less the plots of the final response function appear remarkably similar.

Each of the thirty chronologies was analyzed by the TRL program with the Grid Point Temperature data from January of year t-1 through August of year t to estimate year t indexed ring width. The indices for three prior growth years were also used as predictors, making a total of 23 predictor variables and one predictand variable, the year t ring-width index. For the

Polar and Subpolar Urals most of ten chronologies were analyzed by the UEA program with the proximate meteorological station data (temperature and precipitation) from August of year t-1 through July of year t and for the South Urals from September of year t-1 through August of year t, making a total 27 predictor variables.

Results

Polar Urals. This was the most northerly area and contained five sites. A direct response of the Polar Urals *Larix sibirica* trees as well as *Picea obovata* trees to current June temperatures and especially to current July temperatures was estimated by significant coefficients (0.17-0.29 and 0.27-0.47 correspondingly) for sites ranging from dry and stony soil to stagnant and excessive moist soil habitats. August temperatures did not have a statistically significant influence upon the ring width of current year.

Sometimes there was a positive response to temperature in the prior June, September and April(.15-0.22), while the response to prior July temperatures was significant and negative (0.44). However, because of high colinearity in the climatic variables, the significance of coefficients, when more than 12 months are included in the analysis, may be over estimated.

Current precipitation for June and July was directly related to growth of *Larix sibirica* trees and current April precipitation was directly related to growth of *Picea obovata* trees. A negative response to current June precipitation and a positive response to current July precipitations were significant for *Larix sibirica* trees, while the positive response to current April precipitation appeared to be significant for *Picea obovata* trees.

Knowledge of annual ring-width formation and dates of other phenological changes provide insights as to what seasonal climatic information can influence growth. Thus, during 1961 and 1966 , radial and apical growth, along with other phenological changes, of *Larix sibirica* and *Picea obovata* was observed by the first author in the Polar Urals. Bud swelling and emergence of foliage begins between June 10 and 15. The apical shoot growth begins at the end of June. The first xylem cell formation at the stem base was observed early in July. All of these phases began 2-3 days latter for *Picea obovata* than for *Larix sibirica*. However, in Subarctic regions the calendar date of the above mentioned phenological phases can range as much as 30 days depending upon antecedent climatic conditions.

The formation of latewood for *Larix sibirica* started early in August and stopped between August 15 and 20. *Picea obovata* trees stopped their annual growth around August 10-15. The termination of growth occurred approximately at the same time in different years, so the length of the growing season depended largely on the beginning dates. The earlywood cells made up 70-80% of the annual ring-width.

Since the most cell growth occurs in July, it is natural that temperature during July will exert a great influence on ring width. Temperature effects, such as those in June, may influence other physiological conditions in the trees that lead at a later time to rapid ring-width growth. Thus temperature in June is important even though xylem cell formation at the stem base does not begin until late in the month. For example, high temperatures may favor rapid shoot growth and the development of needles which in turn could produce growth regulators that favor subsequent ring growth (Kramer & Kozlowski 1979).

The fact that August temperatures do not influence the current ring width is at first surprising. However the number of cells is largely determined by this time. Temperature might influence latewood formation which accounts for no more than 20-30% of the ring width, but here again, most of these cells may be produced early in the month so the mean climate of August generally occurs too late in the growing season to affect the current ring-width growth (Fritts 1976).

A positive response to prior September temperature may correspond to favorable conditions for photosynthetic activity and/or bud formation, which can influence stored food reserves and bud primordia affecting the next year's ring width. An inverse response to temperatures in the prior July may reflect the loss of food reserves utilized by the rapid growth of the ring during this time period. If the reserves are shunted into the currently growing ring they will not be available for growth in the following year. A positive response in June of the prior year may have something to do with the high positive autocorrelation in the tree-ring time series. Conditions leading to rapid growth in one year will tend to be followed by rapid growth in the following year.

A negative response of *Larix sibirica* trees to current June precipitation may be caused by inverse relationship between temperature and precipitation. A wet June is often associated with cold temperatures, which reduce all vegetative growth. By July, air temperatures are higher so the cooler temperatures associated with high rainfall are not growth limiting. Summer precipitation does not exert significant influence on *Picea obovata* ring width. However, there is general agreement in that the signs of the response function weights are mostly positive during summer months.

The coefficients for prior growth at only one year's lag are almost always positive and significant (0.31-0.81).

The tree-ring chronologies obtained from the Polar Urals contain much climatic information. The variance explained by climate ranges from 29 to 64% and total variance explained by both climate and prior growth ranges between 69 and 86%. Chronologies of *Larix sibirica* trees growing in stagnant and excessively moist soil contain the most information on variations in climate.

Subpolar Urals. This region contained five sites. The majority of sites exhibited a significant positive response to temperature in the current June through July (Fig. 1). These two variables were the most important ones for the Polar Urals. However, there were differences. The weights for current May temperature were negative and significant for three chronologies. This may suggest that warm temperatures early in the season may hasten bud break and make the trees more susceptible to damage from late frosts. Some weights for winter temperature are significant and negative suggesting possible adverse effects of extremely low temperatures. However the weights for October temperature were significant and positive for four sites.

As in the Polar Urals a negative response of *Larix sibirica* trees to current June precipitations and a positive response to current July precipitation is suggested by significant response function weights. The effect of prior growth at a one-year lag is generally significant. The percent variance reduced by climate ranges between 26 and 46% which is lower than the Polar Ural sites. The total variance explained by both climate and prior growth ranges between 55 and 63%.

As for the Polar Urals, chronologies of *Larix sibirica* trees growing in very moist habitats contained the most information on climate.

North Urals. This region is south of the Subpolar Urals and includes seven sites. The response of both *Larix sibirica* and *Pinus sylvestris* trees to current June through July air temperatures is positive and significant. However, the June temperature response is often larger than the July temperature response, which is different from that of the Polar and subpolar Urals. Four response function weights for May temperature are significant. They were negative for one *Larix sibirica* site and positive for all 3 *Picea obovata* sites in this region. In the latter species the weights for May and July temperature are larger than for June temperature. The weights for April temperature were significant and negative for four sites and positive for one site. As one goes further and further south along the transect, significant positive coefficients are more likely to occur earlier in the season suggesting that physiological activity begins earlier in the southern sites. The weights are negative and significant for temperature in the prior July as in the Polar Ural sites. They are also negative and significant for August in two *Picea obovata* and one *Pinus sylvestris* site.

Prior growth at a lag of one year is directly and significantly correlated with ring width on all North Ural sites. In two cases prior growth at a lag of two years is directly correlated and significant.

The percent variance reduced by climate ranges from 20 to 42%. The one *Pinus sylvestris* chronology reduced the most climatic variance. *Larix sibirica* chronologies were next and *Picea obovata* chronologies reduced the least climatic variance. Climate and prior growth reduced from 48 to 63% of the variance, which was less than the variance reduced for the Polar and Subpolar Ural sites.

South Urals. The Taganai meteorological station situated on the top of the Big Taganai mountain, 1102 m above sea level was used to analyze six sites, and was close (5-15 km) to the tree sites. The remaining six sites are from the Iremel Massif about 90 km South-West from the meteorological station.

Growing season temperature (May through August) was directly related to ring width in both *Larix sibirica* and *Pinus sylvestris* from the Iremel Massif (Fig. 2). The direct temperature response for *Picea obovata* and for *Pinus sylvestris* was weaker with weights significant for four out of 10 and 2 out of 10 sites for June and July. Weights for temperature in March and April were occasionally positive and significant. Inverse relationships between growth and temperature exist for less than 20% of the months from December through April. Half of the weights for temperature in October and November are significant and positive suggesting a late Autumn photosynthetic response to extended warmth.

The weights for precipitation indicate that precipitation at the beginning of the vegetative period (May) and at the end (August) as well as precipitation at the end of the previous season(September) is unfavorable to ring-width growth. This appears to be a linkage of low temperatures to high precipitation events. 23% of the weights for precipitation from October through April and June were significantly and directly correlated with growth. Except for the linkage with low temperatures, precipitation for months other than September, May and August generally favor growth, although the correlation between growth and precipitation is not as high as the correlation between growth and temperature.

Ring-width growth in all but two chronologies is significantly and positively related to the prior year's growth. Two chronologies have significant weights for lag 2 prior growth. The variance explained by climate ranges from 29% to 59%, and with prior growth explains from 32% to 77%.

Conclusions

Chronologies obtained from the Polar Urals appear to have the most information on climate. Trees from the Subpolar, North Urals and South Urals have less and less information on climate. However, there is wide variation in the percentage of variance reduced by climate from site to site. Chronologies of *Pinus sylvestris* and *Larix sibirica* contain more climatic information than chronologies of *Picea obovata* and are likely to produce the best reconstructions of past climate.

Summer air temperatures especially in June and July are highly limiting to ring width growth in the Polar, Subpolar and North Urals. However a positive temperature response is found in May and in April for low-latitude sites, and the weights for June and July temperature are reduced. This may be associated with a lengthening of the period of growth. While high temperature in June and July is associated with high growth in the current season, it is also associated with low growth in the following year. This relationship appears to counteract autocorrelation and suggests that high temperatures may lead to high utilization of food, depletion of stored food reserves and a reduction in the potential for the next year's growth. This may in turn lead to a two-year periodicity in ring width superimposed upon an autoregressive random walk.

At lower latitudes, temperature in April and May becomes relatively more important as the weights for June and July temperature diminish in importance. Inverse temperature relationships are more common and precipitation increases in importance. The average variance explained by climate is 49% for the Polar Urals, 36% for the Subpolar Urals and 28% for the North Urals. The variance explained by climate was 43% for the Taganai Mountains and 44% for the Iremel Massif which may be due to the relatively short distance between the meteorological station and the sites.

It is notable that summer temperature limits ring-width growth in different coniferous species growing on different habitats (ranging from well-drained stony soils to poorly drained and wet soils) along the crest of the Urals in the north.

Ring width is highly dependent upon prior growth. Lag 1 autocorrelation reduces on average for 25% - 30% of the growth variance in the three North Ural groups. In the Taganai Mountains lag 1 autocorrelation reduces only 12% of the growth and in the Iremel Massif it reduces 15% of the growth. The reduction in autocorrelation associated with decreasing latitude of the site has also been noted in North American chronologies (DeWitt & Ames 1978).

The dissimilarities in response function analysis in chronologies on the South Ural sites is confirmed by simple correlation between chronologies in the south and by the lack of synchronous behavior between chronologies in the south. For example, synchrony between chronologies of the same species does not exceed 65%-75% while synchrony between chronologies of different species is low or absent.

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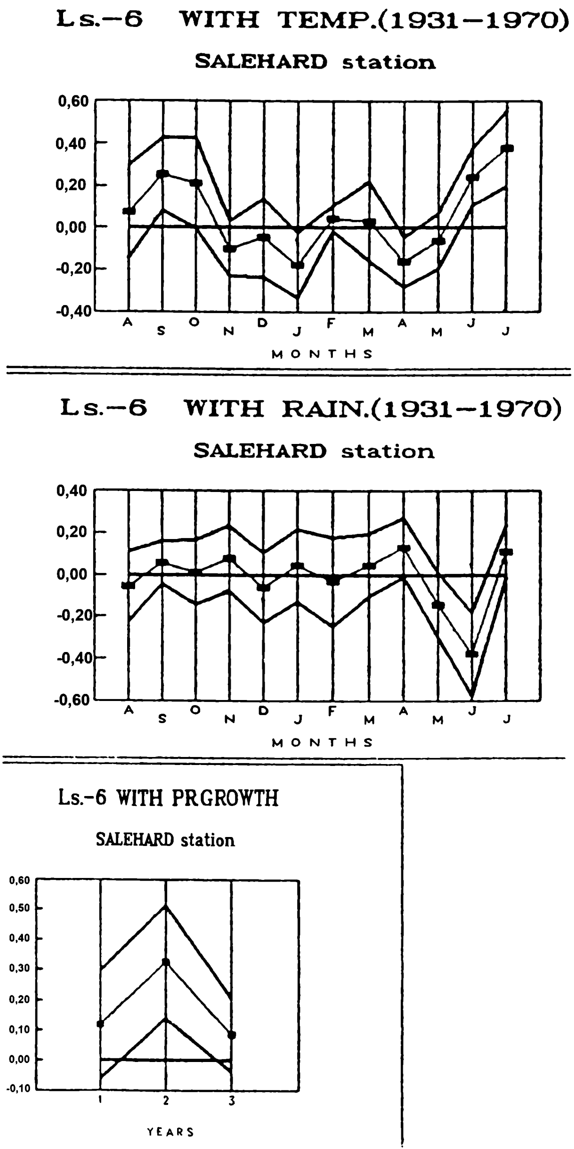

Figure 1. Response function for *Larix sibirica* growing at 550-700 m altitude in the Subpolar Urals, Neroyka Mountain. Variables are monthly temperature and precipitation for August-December of the year prior to growth and for January-July for the year of growth. The 95% confidence limits are shown.

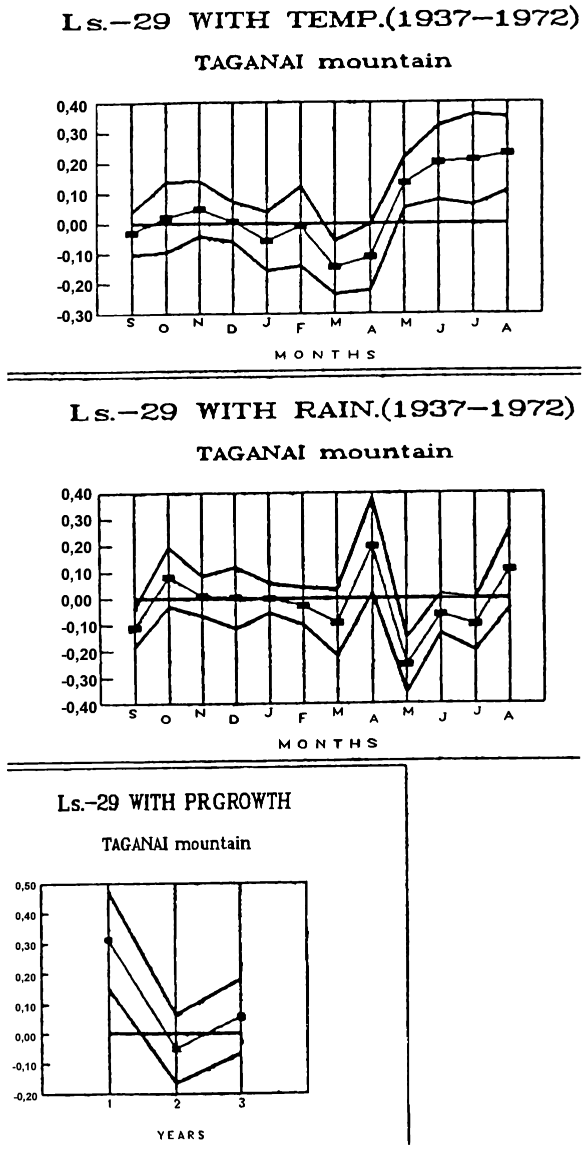

Figure 2. Response function for *Larix sibirica* growing at 1000-1100 m altitude in the Forest steppe of the South Urals, Iremel Massif. Variables are the same as Figure 1.