Dendroindication of Lake Baikal level dynamics

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Abstract. This paper estimates and analyzes water level dynamics in Lake Baikal in the 15th-20th centuries by a method of dendroindication. The endrochronological material for the study was obtained in the Zabaikalsky National Park in 2007. Apart from the chronologies of 2007, the available temporal data sequence is extended by incorporating tree-ring chronologies collected in the 1950s by G. I. Galasy and published in a digest on “Dendrochronological Scales of Soviet Union”. The largest coefficients of positive correlation are found to be between the PinSib10 sample and the cumulative monthly precipitation of February and October and also between the PinSib2 sample and the precipitation of November and the cold season (November-March). A tighter relation between the annual ring increments and the lake level existed before the construction of the hydropower station in the city of Irkutsk. After the construction the increments have also been rather sensitive to changes in the level. The significant correlation between the increment variability and the Lake Baikal level allows the development of a quantitative model of reconstruction of the lake level. The model reproduces up to 60% of the known level variations. The reconstruction shows high level epochs as well as durable epochs of low level. A spectral Fourier analysis reveals cycles of 53, 33, 23, 17, and 11 years in the reconstructed series of the Lake Baikal water level.

1. Introduction
The problem of decrease in the Lake Baikal level is becoming increasingly topical. Judging from daily and monthly data, the level decreased steadily from 1994 to 2015. It should be noted that the decrease in the Lake Baikal level can cause severe ecological problems. It changes the inshore biocenosis, adversely affects the ecosystem of the Selenga River estuary which, in turn, affects the water quality in Lake Baikal [1]. From the data of the 2014 State report on the Lake Baikal conditions, the mean level of the lake decreased by about 50 cm from the beginning of the century [2]. This paper is aimed at estimating and analyzing the dynamics of the Lake Baikal level in the 15th – 20th centuries by a method of dendrochronology. This method was formerly used to reconstruct air and soil temperatures and cumulative precipitation in Baikal region [3-7].

2. Materials and methods
Our dendrochronological material (Pinus Sibirica) was collected in 2007 in the Zabaikalsky National Park at the inflows of the Bolshaya Cheremshanaya and Kedrovaya Rivers to Lake Baikal. According to its climate this territory belongs to the moderate belt with its high humidity, cold summer, and scarce-snowy winter [8]. The dendrochronological samples were collected at different places from the coastline to an appreciable distance from the coast. The sample characteristics are given in Table 1. In each region, 5 to 15 samples of wood have been collected. The boring kerns were taken at a height of
1.3 m from the ground at the northern side of trunks with hollow bores. The samples were taken from healthy trees only. After measuring the tree-ring widths (TRWs) of collected samples, individual tree-ring chronologies were determined by the cross-dating method using the automatic system LINTAB of the program package TSAP. Before constructing common sequences, the TRW sequence of each sample was indexed. The quantitative reconstruction was based on solving the equation of linear regression. Computations were performed with the Data Analysis Program of the Excel package. The statistical significance of the regression model was estimated by the mean approximation error.

| Table 1. Characteristics and age of model trees (TRC1). |
|-----------------------------------------------------|
| **Model tree notification** | **Region** | **Tree height, m** | **Diameter, cm** | **Age, years** | **Distance to shoreline** |
| **PinSib1** | | 16 | 30 | 75 | 50 m (cedar forest) |
| **PinSib 2** | Kedrovaya | 16 | 30 | 90 | ~ 30 m |
| **PinSib 3** | | 12 | 35 | 73 | 50 m (cedar forest) |
| **PinSib 4** | | 14 | 35 | 47 | ~ 30 m |
| **PinSib 5** | | 14 | 30 | 59 | ~ 40 m |
| **PinSib 6** | Bolshaya | 16 | 35 | 88 | ~ 100 m |
| **PinSib 7** | Cheremshanaya | 17 | 40 | 100 | ~ 15 m |
| **PinSib 8** | | 15 | 40 | 80 | ~ 30 m (cedar forest) |
| **PinSib 9** | | 18 | 50 | 80 | 5 m (sand and pebble strand) |
| **PinSib 10** | | 16 | 55 | 71 | ~ 30 m |

Apart from the chronologies of 2007, the tree-ring chronologies (Larix Sibirica and Pinus Sibirica) obtained by G. I. Galasy and the staff of the Laboratory of Botany and Dendrochronology of the Institute of Limnology of the Siberian Branch of the USSR Academy of Sciences in the 1950s and published in the digest “Dendro-Climatic Scales of Soviet Union” [9] were used to extend the sequence. Characteristics of these chronologies are given in Table 2.

| Table 2. Characteristics of tree-ring chronologies (TRC2) [9]. |
|-------------------------------------------------------------|
| **Index** | **Region** | **Scale (years)** | **Place** |
| **PinSib 4** | Lake Baikal, Chivirkui bay, orifice of Big Chivirkui River | 1415-1944 | Right bank of B. Chivirkui River, cedar forest |
| **LarSib3** | Northern part of Lake Baikal, cape Pogonie | 1431-1944 | Pebble strand |
| **LarSib 1** | Lake Baikal, Small Sea, cape Zogduk | 1544-1944 | Pebble strand |
| **LarSib 2** | Northern part of Lake Baikal, cape Kotelnikovsky | 1744-1943 | Boulder and pebble strand |

The degree of the influence of the hydro-climatic factors on tree increments or the relations of the increments with other environmental factors were estimated by the response functions – partial correlation coefficients between the radial increments and the climatic or hydrological factors. For these purposes, we used data on cumulative monthly, seasonal (warm and cold seasons - WSs and CSs) [meteo.ru], and annual precipitation of the meteorological station on the Big Ushkany Island, as
well as data on the Lake Baikal level. The level data were taken from the 2003 State report on the Lake Baikal conditions [11]. The observational series is not homogeneous, because the Lake Baikal level increased abruptly in 1959 when the Irkutsk hydropower station started its operation. The series was homogenized by a method proposed in [12]. The actual values of the level were rescaled with the equation

\[ I_j = \frac{L_j - L_{\text{mean}}}{S_{\text{mean}}} \]

where \( L_j \) is the Lake Baikal level in the \( j \)-th year, \( L_{\text{mean}} \) is the mean level of the lake (computed separately for the epochs before and after the reservoir filling), \( S_{\text{mean}} \) is the dispersion in the series (again estimated separately for the epochs before and after the reservoir filling).

Figure 1 shows the dynamics of the Lake Baikal level from 1900 to 2003.

![Figure 1. Dynamics of Lake Baikal level](image)

1 – actual level; 2 – level rescaled to a homogeneous sequence.

3. Results and discussion

The relation between the hydrological parameters (e.g., river outflows) of the northern hemisphere and the widths of conifer rings has been thoroughly studied for the arid and sub-arid regions and for the regions of sufficient humidity [13-17]. Reconstructing the hydrological characteristics for arid and sub-arid territories with the method of dendrochronology is easier compared to the mild climate zones where several physical and geographical factors can simultaneously influence the tree increments, so that selecting a single dominant factor is problematic. Germination of the trees is mainly controlled by climate conditions. In contrast to the dependence of tree germination on climate parameters (temperature, precipitation), which directly influence the annual increments, its dependence on hydrological characteristics (outflow, inflow, level) is less certain and region-dependent. The annual river outflow is composed of a variety of climatic and physical-geographical parameters. The trees of a watershed are often sensitive to some of the hydrological conditions. Most stable relations between tree increments and hydrological characteristics are typical of the regions of insufficient humidity.

Reconstruction of the level of lakes fed by a river system was a subject of several studies. The Lake Athabaska level was reconstructed with data on the widths of rings of the trees of the lake watershed [18]. Germination of trees is related to the lake level due to the sensitivity of trees to the soil humidity in the watershed.

As already mentioned, the response of the tree-ring increments to climatic or hydrological variations was estimated by calculating the correlation coefficients. Factors controlling the increments
can be revealed in this way. Reliable quantitative reconstructions are known to be possible only if a certain well-defined controlling factor is found [19].

Figures 2 and 3 show the responses of the tree-ring widths to the atmospheric precipitation and the Lake Baikal level, respectively.

**Figure 2.** Correlation coefficients between monthly precipitation of meteorological station on B. Ushkany Island and widths of tree-rings TRC1.

It can be seen that the largest positive correlation coefficients are between the model sample PinSib10 and the precipitation of February or October, and between the sample PinSib2 and the precipitation of November or the cool season (CS (November-March)). The inverse relation is observed between the sample PinSib1 and the October precipitation, and also between the sample PinSib9 and the December precipitation. The positive relation with the precipitation of February can possibly be explained by heat storage in the near-root system, because the snow coverage facilitates the storage. It also increases the soil humidity in the pre-vegetation season.

Figure 3 shows the responses of the tree-ring widths to the Lake Baikal level for TRC1 (Figure 3A) and TRC2 (Figure 3B).

The histograms of Figure 3 show that the response of the tree-ring widths to the Lake Baikal level can either be positive or negative. The correlation coefficients in this case are larger in absolute values compared to the correlation between the air temperature or precipitation and the ring widths. A positive response is observed for the trees at relatively large distances from the coast, while the ring series of the trees growing close to the water line react negatively to increase in the water level (coast and root degradation, excessive humidity). Before the construction of the hydro-power station in Irkutsk, the response of the ring widths to the lake level was relatively strong, although after that the response is also not weak.

A comparative analysis of the responses in the radial increments to the Lake Baikal level revealed TRCs with the largest correlation coefficients, which are shown by black color in Fig. 3. This allows using two chronologies for searching regression equations appropriate for the reconstruction of the Lake Baikal level in the pre-instrumental observation epoch. The quantitative reconstruction is based on solving the equation of linear regression. The computations were performed with the Data Analysis...
Package of the Excel Program. The statistical significance of the regression model was estimated with the mean approximation error.

\[ Y = a + b x \]

where \( b \) is the coefficient measuring the variation rate of the reconstructed parameter (lake level), \( x \) is the independent variable (tree-ring width in this case), and \( a \) is a constant.

Figure 4 shows the reconstructed and real levels of Lake Baikal rescaled to a uniform sequence.

Consideration of Figure 4 shows that the widths of tree rings indicate minima and maxima in the lake level, although they somewhat ‘smooth’ the minima/maxima. We formerly observed a similar case when reconstructing the cumulative inflow to Lake Baikal [20]. A comparison of the
reconstructed and instrumentally measured cumulative inflows shows the coincidence of major peaks in their time dependences, but the peaks in the reconstructed profile are smaller. The 11-year running mean values also show good convergence. Minima in the cumulative inflows in Lake Baikal were observed in the 80s of the 19th century and in the 20s, 50s, and 80s of the 20th century.

The reconstruction model reproduces up to 60% of the variations in the lake level. The reconstruction indicates the epochs of high level (1471-1477, 1511-1523, 1537-1542, 1678-1682, 1693-1697, 1792-1794) and also rather durable epochs of low level (1418-1465, 1490-1508, 1553-1561, 1613-1617, 1641-1652, 1685-1689, 1739-1742, 1810-1814, 1860-1865, 1889-1894, 1919-1928).

A Fourier analysis of the reconstructed series reveals cycles with periods of 53, 33, 23, 17, and 11 years in the Lake Baikal level. The cyclic variations we found can be caused by the influence of either the 11-year solar cycle or the so-called Bruckner cycle (about 35 years) in the regional dampness [21].

The results show that the epochs of rather low level in Lake Baikal had occurred repeatedly, but the normal level always recovered after that. Our results generally confirm the earlier studies of the Lake Baikal level dynamics [22, 11].

4. Conclusions
1. Both positive and negative responses of tree-ring widths to variations in the Lake Baikal water level have been observed, the absolute values of the correlation coefficients being larger compared to those of the correlations between air temperature, atmospheric precipitation, and tree-ring widths.
2. A positive response has been found for trees growing at considerable distances from the coastline, while trees close to the line experience negative influence of the increased water level (coast and root degradation, excessive humidity).
3. The reconstruction model reproduces up to 60% of variations in the lake level. The reconstruction shows both epochs of high water level and rather durable epochs of low level.
4. A Fourier analysis of the reconstructed series of the Lake Baikal level revealed cyclic variations with periods of 53, 33, 23, 17, and 11 years. The cumulative inflow in Lake Baikal also shows cycles of 30-50 years.
5. Epochs of rather low level of the lake water repeatedly occurred in the past, but the normal level soon recovered.
6. The method of dendrochronology has shown its robustness in the analysis of Lake Baikal level dynamics. The reconstruction of certain hydro-climatic elements allows an extension of the temporal sequences and improves the forecasting. Our results supplement the available information on the previous variations in the lake level, which is important for understanding the mechanisms and causes of regional and global changes in the hydrological conditions.

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