Supplementary Materials

Supplementary Material (SM) for the manuscript titled "Unprecedented acceleration of winter discharge of Upper Yenisei River inferred from tree rings" by Panyushkina *et al* includes a) two sections covering details on methodology of the tree-ring chronology calculation (SM1) and discharge regression modeling (SM2), b) two tables (ST1-ST2) and seven figures (SF1..SF7) cited in the main text of the paper, and c) reference list for the supplemented data.

An excel file is available under the name "SM-Panyushkinaetal.xlsx" which is a time series matrix from the regression models covering the period 1700-2019. The time series include two Kyzyl-gaged discharge predictors (Nov-Apr low water season and Oct-Sept water year), eight tree-ring chronology-predicants as listed in Table 1, and two reconstructed Yenisei discharges (Nov-Apr and Oct-Sept) at the Kyzyl gauge as shown in Fig. 2.

SM1. Calculation of tree-ring chronology

Each time series for an individual tree was fit with a 100%N cubic smoothing spline, defined as a spline with a frequency response of 0.5 at the wavelength equal to the length of the series (Cook and Peters 1981). Tree indices were computed as the ratio of measured width to the fitted line, and the site chronology was computed as the biweight mean of available indices in a given year. The site chronology was then variance-stabilized to reduce distortion of chronology variance caused by averaging over a time-varying number of core indices (Osborn *et al* 1997). A final step of variance stabilization was applied to the site chronology to remove any remaining trend in variance on wavelengths on the order of the length of the chronology. This was accomplished by fitting a spline to the time series of absolute departures of the chronology from its long-term mean, removing the trend by subtracting the trend line from the absolute departures, and restoring the original sign of those departures (Meko *et al* 1993). After variance stabilization, chronologies were re-centered if needed to have a long-term mean of exactly 1.0. All except two of the 36 chronologies are *Larix sibirica*; the other two are *Pinus sibirica*. Sites were sampled between 1997 and 2019. All are *Larix sibirica*, and several have start years much earlier than 1700 CE. The maximum number of trees at a site ranges from 10 to 24, and for all except two sites the expressed population signal (EPS, Wigley *et al* 1984) reaches the critical value of 0.85 – indicating adequate sample size to represent the population growth signal – before the mid-1700s.

SM2: Regression modeling

Including too many potential predictors in the model has the potential to seriously bias the R^2 value, and so here we limit the size of the pool to 1/5 the number of calibration years, or 14 potential predictors (Rencher and Pun 1980). To reduce the pool size to 14 potential predictors, chronologies and their lags were screened by correlation against winter (Nov-Apr) and water-year (Oct-Sep) discharge and the pool was allowed to contain only those tree-ring series with the highest 14 absolute correlations with discharge. Such screening yielded critical absolute correlations of r=0.249 for Nov-Apr and r=0.230 for Sep-Oct. Both thresholds are close to the theoretical threshold of r=0.23 for significant (0.05 level) Pearson correlation for a sample size of 70 observations. An additional restriction in selecting the 14 strongest correlations required that the correlation was "stable" from the first to second half of the 1927-1996 test period. Stability was judged by a non-significant (0.05 level) difference in correlations for the first and second halves by a difference-of-correlation test (Snedecor and Cochrane 1989).

At each step, the model was cross-validated by leave-5-out cross-validation (Meko, 1997), which ensures no tree-ring data used to provide a cross-validation prediction are also used in calibrating the cross-validation model. Entry of predictors into the model was stopped whenever an additional step would yield decreased validation accuracy as judged by the reduction of error statistic (RE, Fritts *et al* 1990). Models were also subject to an analysis of residuals (Weisberg, 1985) to check for possible violations of regression assumptions on normality and non-autocorrelation of residuals, and on constancy of residual variance. These were checked with histograms, the autocorrelation function of residuals, the Durbin-Watson (DW) statistic and a scatter plot of residuals on predicted values.

Equation S1: The linear regression equation of reconstructed model for Nov–Apr low water season discharge of the Yenisei River at the Kyzyl gauge.

$$Q_{Nov\text{-}Apr} = 332.63 + (-82.99\hat{x}_{mong33t}) + (88.43\hat{x}_{HONt-1}) + (43.05\hat{x}_{CHGt}) + (-59.59\ \hat{x}_{russ230t+1}) + (-50.02\hat{x}_{russ258t})$$

where x are the tree-ring indices of indicated tree-ring chronologies and Q is the reconstructed Nov-Apr discharge.

Equation S2: The linear regression equation of reconstructed model for Oct-Sept water-year season discharge of the Yenisei River at the Kyzyl gauge.

$$Q_{Oct\text{-}Sep} = 906.96 + (122.63\hat{x}_{SHAt+1}) + (-176.72\hat{x}_{russ22t}) + (67.28\hat{x}_{CHGt}) + (89.23\ \hat{x}_{russ249t-1})$$

where x are the tree-ring indices of indicated tree-ring chronologies and Q is the reconstructed Oct-Sept discharge.

Tables

Table S1: *Statistics[a] of observed and reconstructed discharge of the Yenisei River at Kyzyl gauge.*

Season	Mean	Median	Std. Dev.
Nov-Apr			
Observed	285	278	65
Modeled 1927-1997	263	261	40
Modeled 1789-1997	276	277	36
Oct-Sept			
Observed	1023	1009	146
Modeled 1927-2000	1020	1021	75
Modeled 1798-2000	1017	1013	71

[a]Mean, median and standard deviation in m^3/sec.

Table S2. *Statistics[a] of monthly observed and WBM simulated discharge of the Yenisei River at Kyzyl gauge.*

Time Period	NSE	Average Discharge	R
1927-51	-0.12	991.86	0.75
1952-72	0.33	1059.56	0.75
1973-2018	0.35	1001.70	0.75

[*]NSE is Nash-Sutcliffe Efficiency, value >0 indicates that the model outperforms the time series average); Average Discharge is observed discharge at Kyzyl gauge (9002) in m^3/s; R- coefficient of correlation.

Figures

Figure S1: *Example of monthly and seasonal correlations between tree-ring chronologies and climate data: a) CHG site and Kyzyl station, b) Mong33 and CRUE grid, and c) Russ 249 and Abakan station. Output from program Seascorr shows correlations with temperature (red) and precipitation (blue). Top panel is Pearson correlation and bottom is partial correlations. Results shown for "seasons" of length 1, 3, and 6 months with variable ending month. Significance estimated by Monte Carlo method (Meko et al. 2011) is color coded for two α levels.*

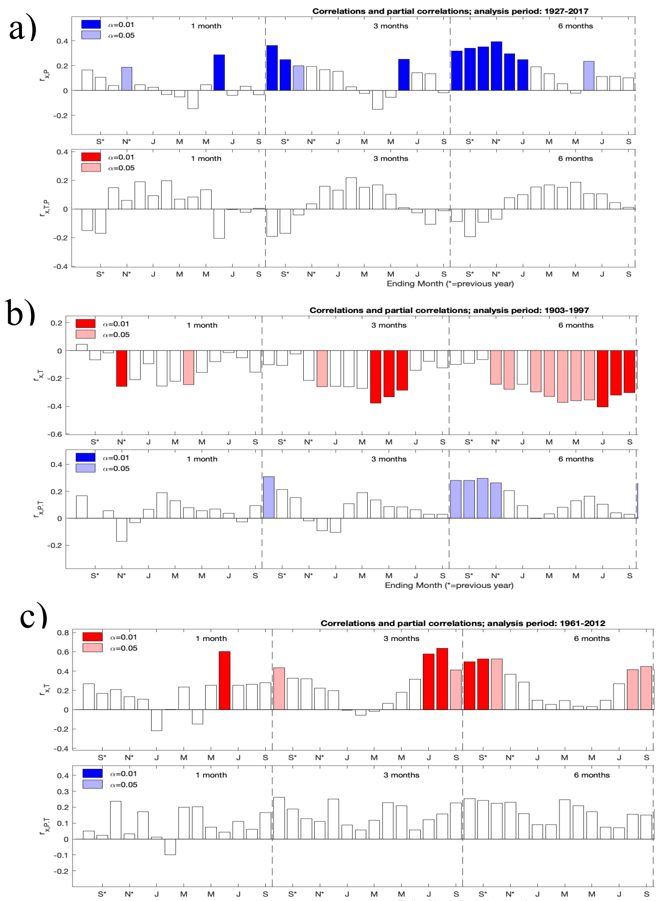
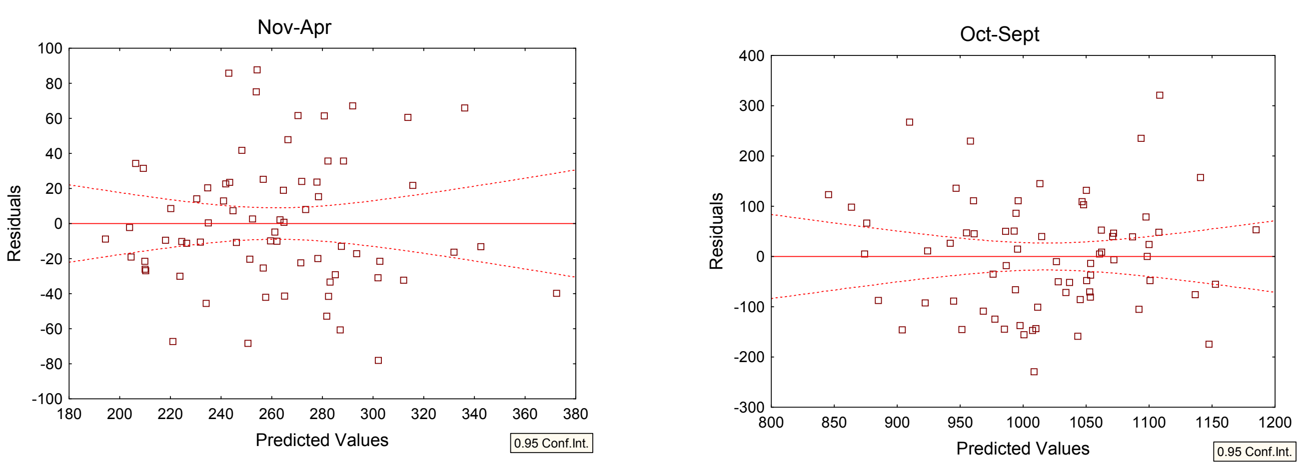


Figure S2: Scatter plot of regression residuals for models to reconstruct Nov-Apr and Oct-Sept discharge from the tree rings.



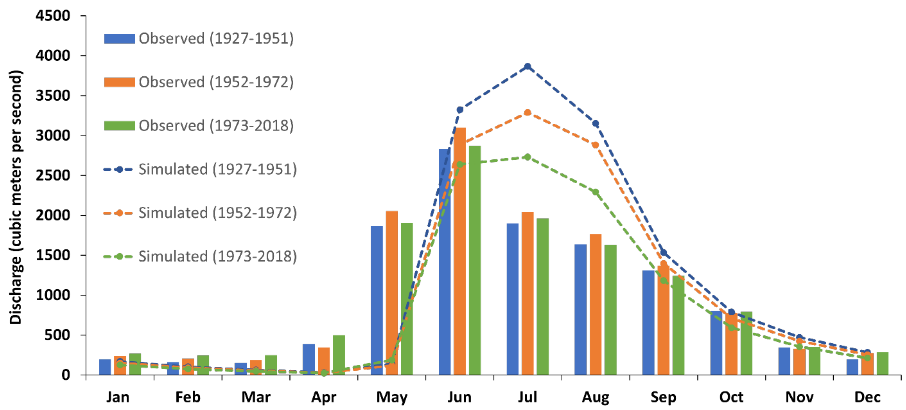


Figure S3: *Observed (bars) and WBM simulated (dashed lines) monthly discharge at the Kyzyl gauge (#9002) for the time periods 1927-1951, 1952-1972, and 1973-2018.*

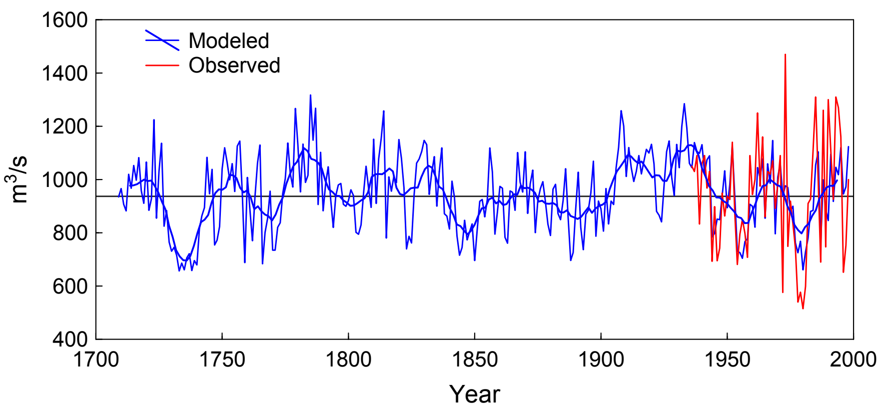


Figure S4: *Annual discharge (Jan-Dec) of the Selenga River reconstructed from tree rings by Andreev et al (2016) for the period 1709-1998. Selenga is a 992 km long flow draining 447,000 km^2 area, the second upper reach subregion of the Yenisei River near Lake Baikal.*

Figure S5: *Linear regression slope of CRU2 annual temperature fields in Eurasia calculated for 1940-2018 (a) and 1960-2018 (b).*

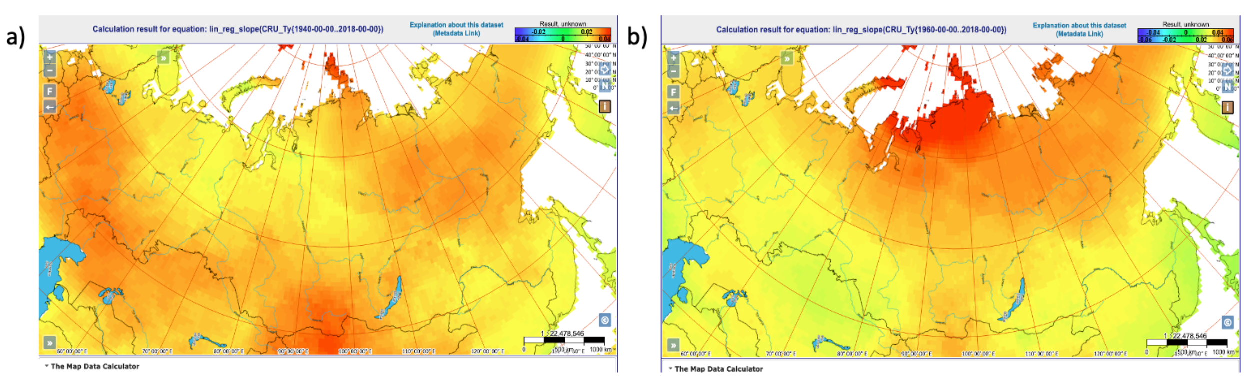


Figure S6: *Map of changes in the maximum active layer depth across South Siberia derived from MODIS land surface temperature data and ERA5 reanalysis (Obu et al 2020). The slope of the linear regression trend is calculated for each grid cell over the period 2000-2018 (https://trish.sr.unh.edu). Red and blue colors show positive and negative trends respectively. Black contour is the sub-basin of hydrometric gauge "Yenisei at Kysyl"- representative of the Yenisei River headwaters.*

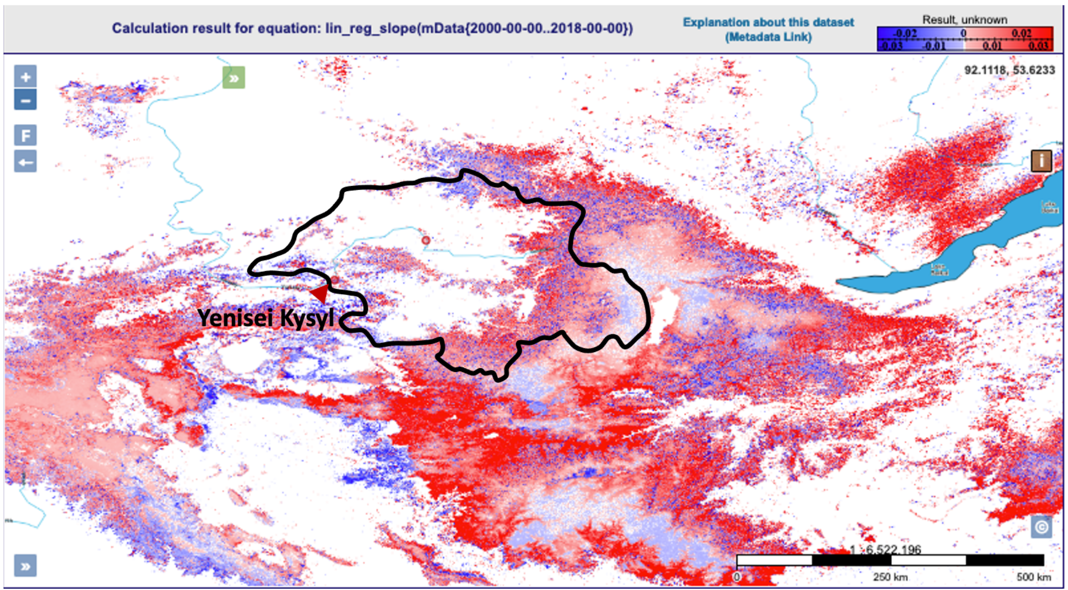
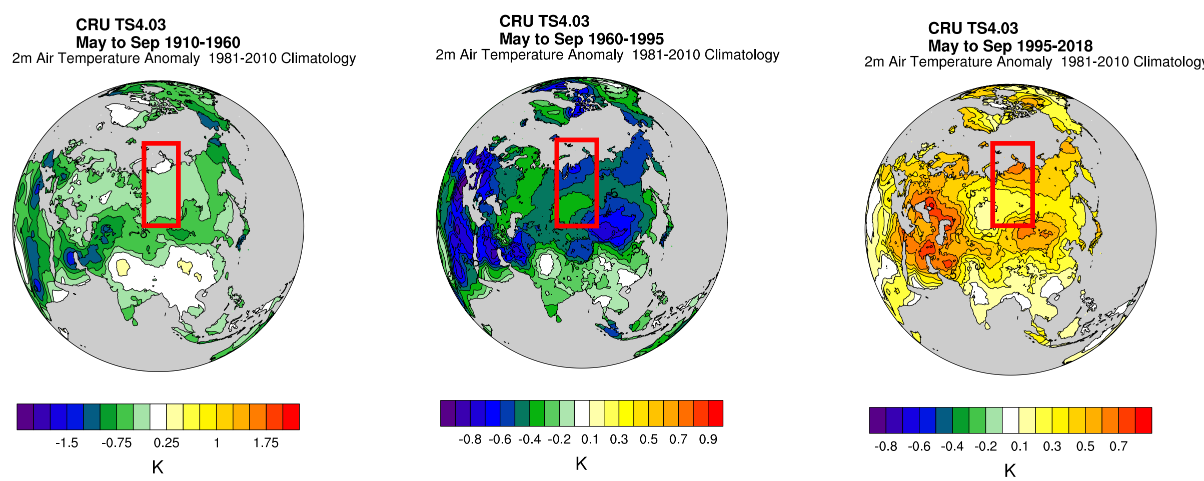
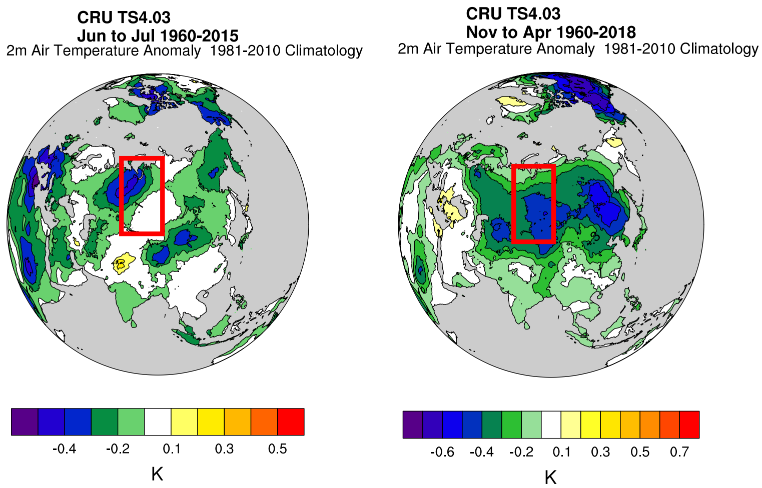


Figure S7: *(a) Summer (May-Sept) air temperature anomaly over Eurasia for the intervals 1910-1960, 1960-1995 and 1995-2015. (b) Summer (Jun-Jul) and winter (Nov-Apr) air temperature anomaly over Eurasia for the intervals 1960-2015 and 1960-2018, respectively. Red rectangle marks the Yenisei River basin.*

a)



b)



Supplementary Materials References

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