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Recent Eurasian river discharge to the Arctic Ocean in the context of longer-term dendrohydrological records

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[1] Mapped correlations between annual discharges (AD 1938–1990) of the major Eurasian rivers entering the Arctic Ocean (Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma) demonstrate a positive relationship between discharge and the Palmer Drought Severity Index (PDSI) within the individual basins and more distant areas. The relationship between recent discharge and PDSI supports the application of dendrohydrological modeling to produce reconstructions of discharge extending back before the 20th century. The dendrohydrologic models explain from 41% (Yenisey) to 55% (Pechora) of the observed variability of flow in the individual basins and 39% of the total combined discharge. Discharge reconstructions for the period AD 1800–1990 indicate that there is no long-term monotonic trend toward higher discharge over the past 200 years. Reconstructed annual discharge for the individual rivers and the total discharge from all the rivers experienced in the 20th century are within the bounds of natural variability experienced over the past 200 years. The S. Dvina, Pechora, Ob, and Kolyma reconstructions do display significant multidecadal variability in discharge similar to that observed in the North Atlantic, North Pacific, and Northern Hemisphere climatic parameters. Although the translation of such variability to the river discharges remains uncertain, the presence of multidecadal variability makes it more difficult to detect or ascribe annual discharge changes that may be attributable to global warming.

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1. Introduction

[2] Sustained increases of river discharge from northern Eurasia into the Arctic Ocean basin could be a key diagnostic of global climate warming. In addition, through its impact on North Atlantic Deep Water (NADW) formation, increased input of freshwater to the Arctic Ocean might potentially alter ocean circulation and global climate [*Aagaard and Carmack*, 1989; *Broecker*, 1997; *Manabe and Stouffer*, 1994; *Peterson et al.*, 2002; *Rahmstorf*, 2002; *Vellinga and Wood*, 2002; *Arnell*, 2005]. For this reason, detecting and understanding the natural variability and genesis of such increases in high-latitude river discharge is of critical importance to climatic change research [*Vörösmarty et al.*, 2001]. Increases in northern Eurasian discharge have been linked to enhanced transfer of moisture to the northern high latitudes resulting from altered climate patterns associated with global warming [*Peterson et al.*, 2002; *McClelland et al.*, 2004]. On a regional scale, permafrost thawing could also produce a transient increase in freshwater delivery to northern Eurasian Rivers, although the duration and intensity of warming required for this remains unclear. Similarly, deforestation due to increased fire frequency could promote increased runoff and enhanced discharge [*McClelland et al.*, 2004]. A growing influence of groundwater sources has also been proposed to explain some of the Eurasian discharge increases [*Smith et al.*, 2007].

[3] Understanding the potential drivers and impacts of increased freshwater discharge from Eurasia has become more critical following recent studies that indicate such increases in discharge may have occurred in recent decades. Work by *Peterson et al.* [2002] suggested that the net discharge from the six largest Eurasian rivers flowing into the Arctic Ocean (Severnaya Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma) increased by $\sim$128 km^3 a^{-1} ($\sim$7%) from AD 1936 to 1999. The greatest relative increase in discharge was observed in the winter (December, January, and February). Although subsequent analysis of discharge records suggests that the construction and operation of large dams may have altered the seasonal distribution of discharge [*Yang et al.*, 2002, 2004; *Ye et al.*, 2003; *McClelland et al.*, 2004], an overall annual increase in discharge appears to be a robust feature of the recent hydrology [*McClelland et al.*, 2004]. *Smith et al.* [2007] find baseflow increases since $\sim$AD 1985 to be largely unprecedented in the instrumental record. In addition, there is some evidence of contemporaneous freshening of the North Atlantic in recent decades [*Curry et al.*, 2003; *Curry and Mauritzen*, 2005].

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Figure 1. Drainage basins of the major northern Eurasian rivers and gauging stations used in the analyses.

[4] It has been argued the discharge gains experienced in the late 20th century are related to large-scale climatic patterns associated with climate warming [*Peterson et al.*, 2002; *McClelland et al.*, 2004]. Although *Peterson et al.* [2002] correlated the increasing discharge with increasing global temperatures and the North Atlantic Oscillation Index (NAO), resolving the exact nature of the climatic changes influencing flow, and how the impacts of climate change are mediated through processes such as changes in snowmelt timing, permafrost alteration and vegetation change remains a complex problem [*Yang et al.*, 2002, 2004; *Ye et al.*, 2003; *McClelland et al.*, 2004; *Gedney et al.*, 2006]. Key limitations include the generally sparse nature of the Arctic climate station network and the uncertainties associated with Arctic precipitation records [*Serreze et al.*, 2002; *Yang et al.*, 2001; *Serreze and Etringer*, 2003; *Pavelsky and Smith*, 2006]. Another critical limitation is the brief span of the discharge records themselves. With a common period extending less than 60 years into the past, the short instrumental discharge records make it impossible to answer the central question of whether or not the discharge gains of past decades are unprecedented in this and recent centuries, possibly reflecting global warming, or if they lie within the boundaries of typical longer-term natural variability. Furthermore, the discharge records from northern Eurasian rivers are too short to test for the significance of low-frequency modes of variability or long-term associations with the NAO and the Arctic Oscillation (AO) which vary at decadal to multidecadal timescales [*Cook et al.*, 2002; *D'Arrigo et al.*, 2003; *Polyakov et al.*, 2005]. Given the impact of North Atlantic conditions on northern Eurasian climate in both winter and summer [*Ogi et al.*, 2003] and the influence of river discharge on North Atlantic salinity it is conceivable that significant feedbacks link the two systems and contribute to defining such modes of variability.

[5] One means of extending short hydrological records is provided by the analysis of tree rings. In many cases, the radial growth of trees, even at higher latitudes, is sensitive to hydroclimatological parameters, such as seasonal precipitation or evaporation rates, that influence river discharge and can therefore be used to reconstruct discharge variations related to climate [*Stockton and Fritts*, 1973; *Pederson et al.*, 2001; *Case and MacDonald*, 2003]. Although trees from the Arctic treeline are typically sensitive to temperature, stands in the boreal forest or other upper river environments can also display significant sensitivity to moisture [e.g., *Larsen and MacDonald*, 1995; *Szeicz and MacDonald*, 1996; *Barber et al.*, 2000; *Pederson et al.*, 2001; *Drobyshev and Niklasson*, 2004]. In this paper we illustrate that discharge variability of the largest northern Eurasian rivers is correlated with broad geographic-scale variations in aridity as captured by the Palmer Drought Severity Index (PDSI [*Palmer*, 1965]). PDSI is a synthetic hydrometeorological index incorporating precipitation, evaporation and soil moisture storage that is often highly correlated with tree ring width variations and river discharge [*Cook et al.*, 1999; *Dai et al.*, 2004]. We then use tree ring records from a network of sites extending across northern Eurasia to provide reconstructions of annual discharge for the October to September water year for the major Eurasian rivers entering the Arctic Ocean (S. Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma). The reconstructions extend back to AD 1800. We compare the discharge over recent decades (up to AD 1990) to past discharge variability. We also compare annual discharge to long-term reconstructions of Siberia temperatures, the AO and the NAO. Wavelet analysis is used to examine the discharge records for evidence of persistent modes of low-frequency variability.

2. Data and Methods

[6] The river discharge records used in this analysis were provided by J.W. McClelland for gauging stations near the mouths of the six major Eurasian rivers entering the Arctic Ocean (Figure 1). The stations are at Ust' Pinega (S. Dvina River), Ust' Tsil'ma (Pechora River), Salekhard (Ob' River), Igarka (Yenisey River), Kyusyur (Lena River), and Kolymskoye (Kolyma River). The Ob', Yenisey, Lena, and Kolyma all support major dams and the discharge records

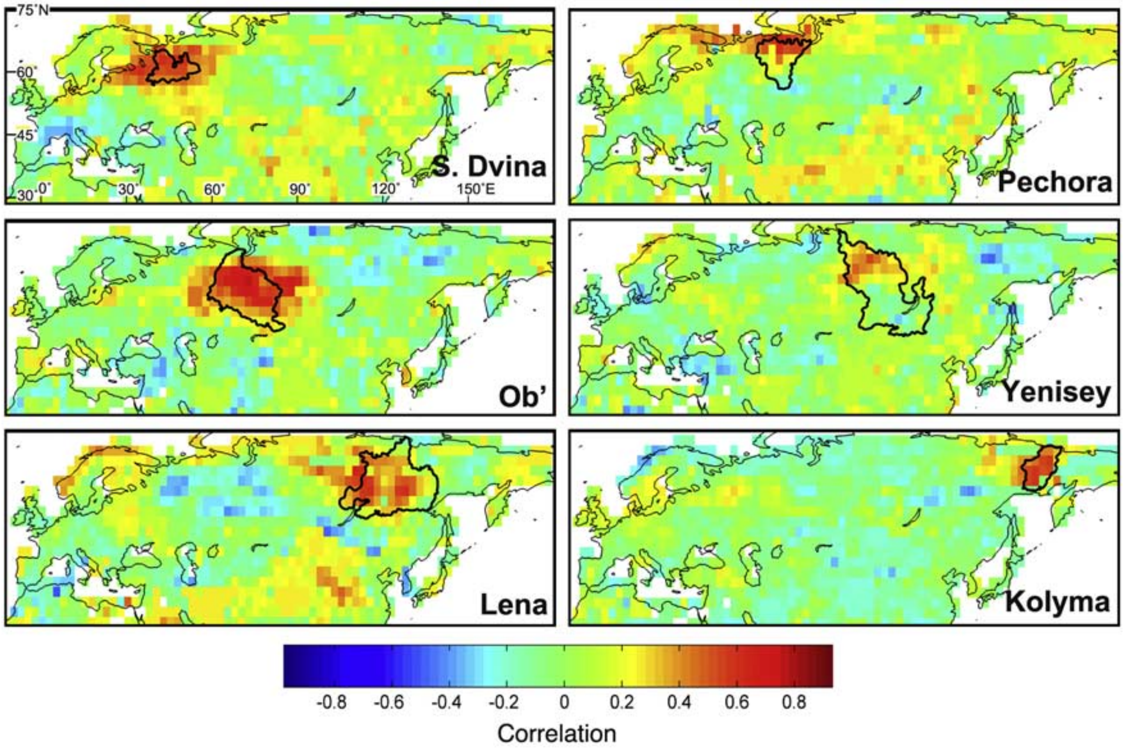

Figure 2. Correlations between annual water year discharges from the major northern Eurasian rivers and annual water year Palmer Drought Severity Index (PDSI). Outlines of the river drainage basins are indicated in black.

have been corrected for this. The influence of reservoirs is further mitigated by our use of annual discharge totals, as the primary effect of dams is to alter flow seasonality but not total annual flow [*McClelland et al.*, 2004]. The S. Dvina and Pechora watersheds do not have comparable dams. The data and details on derivation of the discharge records and corrections for the impact of major dams are available from *Peterson et al.* [2002] and *McClelland et al.* [2004]. Water year annual discharge (October to September) was calculated for the individual rivers and for all rivers combined for the common period of AD 1938–1990. Gridded annual PDSI values for the common period AD 1938–1990 were extracted for Eurasia from the global PDSI data set produced by *Dai et al.* [1998, 2004] and are available from NOAA at www.cdc.noaa.gov/cdc/data.pdsi.html. The gridded PDSI values are calculated at a spatial resolution 2.5° by 2.5°. Although the regional precipitation and temperature data sets used to calculate the gridded PDSI estimates contain some errors, a number of measures were taken to minimize data inhomogeneities [*Dai et al.*, 2004]. To test the general veracity of the PDSI time series, *Dai et al.* [2004] compared the values with observed soil moisture values obtained from North America and Eurasia. For the northern Eurasian study area, the correlations reported between PDSI anomalies and observed soil moisture anomalies ranged from $r = 0.54$ to $r = 0.71$ ($p \leq 0.05$). They also found that the estimated PDSI values correlate significantly with variations in discharge of the Lena and S. Dvina rivers [*Dai et al.*, 2004]. Reconstructed Siberian summer temperatures, NAO (winter) and AO (summer) time series that extend back past AD 1800 have been produced by *Briffa et al.* [1995], *Cook et al.* [2002], and *D'Arrigo et al.* [2003], respectively. These data are available from NOAA at www.ncdc.noaa.gov/paleo/datalist.html. The reconstructed series were used for comparison with our discharge reconstructions.

[7] The tree ring chronologies used to examine the relations between flow and ring width variations and produce the dendrohydrological models were obtained from the International Tree-Ring Data Bank housed by NOAA (http://www.ncdc.noaa.gov/paleo/treering.html). We utilized the standard ring width chronologies provided online by the data bank. The standard chronologies are unitless indices which present a nearly stable mean and variance. The standard chronologies are constructed by combining the individual tree ring width series from all radii measured at each individual site after biological growth trends have been

Table 1. Correlations (r) Between Observed Annual Discharge of the Major Northern Eurasian Rivers Over the Common Period AD 1938–1990[a]

	S. Dvina	Pechora	Ob'	Yenisey	Lena
Dvina					
Pechora	**0.370**				
Ob'	0.070	0.086			
Yenisey	0.059	0.193	**0.321**		
Lena	−0.024	0.200	−0.127	**0.374**	
Kolyma	−0.046	−0.095	−0.108	−0.103	**−0.285**

[a] Bold values significant at $p \leq 0.05$. The significant values have been calculated to account for the loss of degrees of freedom due to autocorrelation in the time series [*Dawdy and Matalas*, 1964].

Table 2. Statistics for Dendrohydrologic Models for the Estimation of Water Year Discharge Calibrated Using Gauge Data for AD 1938–1990[a]

	Total	S. Dvina	Pechora	Ob'	Yenisey	Lena	Kolyma
SITES	33	17	16	34	32	28	27
MEAN RADII	19	17	16	21	20	20	20
CVSE	35266	4892	3986	18651	10879	19457	5864
r^2	0.3902	0.4377	0.4129	0.5111	0.5551	0.4277	0.5354
MEAN OBS	698992	37896	41065	158865	223205	199760	38199
MEAN REC	703390	37441	40661	157651	224364	203536	38329

[a] SITES and MEAN RADII indicate the total of number of tree ring site chronologies selected by the reconstruction model and the mean number of radii in these individual chronologies at AD 1799. CVSE is the cross-validation standard error of the model (see text and *Hidalgo et al.* [2000]). The correlation coefficient is r^2 (all r^2 values indicate significance of $p \leq 0.05$). MEAN OBS is the observed mean of the discharge series (AD 1938–1990). MEAN REC is the mean of the full (AD 1800–1990) reconstructed series.

removed by straight line or negative exponential detrending. Details on detrending approaches and standard chronology construction can be found in the work of *Cook and Kairiukstis* [1990]. Typically, tree ring chronologies consist of a large number of radii for recent years and this number decreases back in time. There remains a potential for changes in variance and declining subsample signal strength over the length of the chronologies due to the decreasing sample size of radii incorporated in the older parts of the chronology [*Briffa and Jones*, 1990; *Osborn et al.*, 1997]. To mitigate against these factors, we only used the portion of the standard chronologies extending over the relatively recent period from AD 1799–1991. Although this renders relatively short reconstructions, it allowed us to preserve as closely as possible the original environmental signals and potential periodicities in variability at high and low frequencies by avoiding further detrending of the chronologies or manipulations of their variance. We also limited our data set to chronologies which contained four or more radii at AD 1799. However, only one site had only four radii at AD 1799, and the vast majority of the chronologies incorporated far more radii. The average minimum number of radii at AD 1799 in the chronologies used in our models is approximately 20, and some chronologies contain over 30 radii at AD 1799. In addition, the large number of different chronologies used in our models (16 to 34) means that the models are based on hundreds of individual radii and further mitigates against variance changes in any one chronology impacting the results. The resulting network of 129 chronologies extends across northern Europe and Asia and incorporates a wide variety of species. Georeference information and details on the specific chronologies used in our reconstructions are available as supporting online documentation (Table S1 and Data Set S1)[1].

[8] Dendrohydrological models to estimate annual average discharge (October–September water year) for the six major rivers were developed using the Principal Components Analysis (PCA) based regression and cross-validation statistical approach of *Hidalgo et al.* [2000]. The modeling process selects a subset of predictor sites from the 129-site tree ring network on the basis of the partial correlations between tree ring widths and discharge. The procedure then uses PCA to extract the common signal from the subset that is most highly correlated with discharge. We have modified the original *Hidalgo et al* [2000] algorithm so that it now uses negatively correlated and positively correlated tree ring chronologies. The models use both contemporaneous values for tree ring growth and river flow and 1-year forward and backward lagged values of tree ring growth to capture persistence in the relationship between moisture conditions and ring size. More than 8000 possible model configurations were tested corresponding to particular subsets of chronologies used as predictors. Acceptable models had to pass the cross-validation statistical tests outlined by *Hidalgo et al.* [2000] in which a sign test and stability test were performed. The sign test was used to check that in the acceptable models the sign of the partial correlation between streamflow and each tree ring site was consistent with the sign of the coefficients in the regression. The PCs in the regression were introduced sequentially without skipping components [*Garen*, 1992]. Finally, a time stability check was performed on the model to make sure the first half of the data uses the same number of PCs compared to the case when the model is calibrated using the second half of the data. A delete three procedure was used to compute the cross validation standard error. For any given year, the previous, the current and next year were removed from the streamflow and tree ring data sets. The remaining tree ring data was used in a PCA and regressed to the remaining streamflow data set. The linear regression was used to obtain an independent estimate of the deleted current year. The process is repeated for all the years until an independent time series of estimated streamflow is obtained. The standard error between this time series and the observed streamflow is the cross-validation standard error. The model with the lowest cross-validation standard error (CVSE) was selected for calibration. The dendrohydrological models were calibrated and statistically verified over a common period of observed discharge records of AD 1938–1990.

[9] In order to test for periodic to quasi-periodic variability in discharge, and examine the strength of such variability over the span of the reconstructions, the estimated discharges were subjected to wavelet analysis [*Torrence and Compo*, 1998]. The significance ($p \leq 0.10$) of peaks in the wavelet power spectrum was tested against an autoregressive red noise background spectrum.

3. Results

3.1. Recent PDSI-Discharge Relations

[10] The spatial correlations between annual river discharge in all the major basins and annual PDSI demonstrate

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[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/jg/2006jg000333.

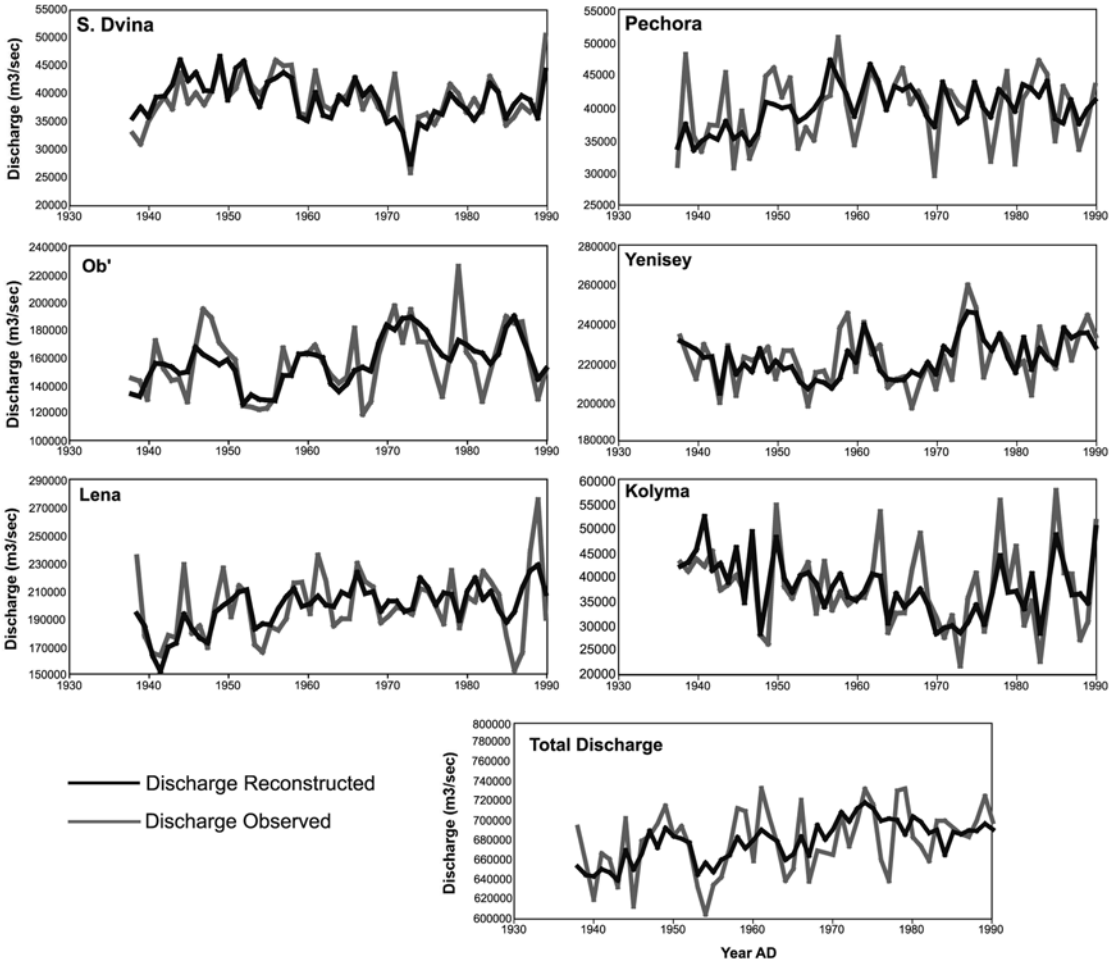

Figure 3. Comparison of observed (dam corrected) annual water year discharges and dendrohydrologically estimated annual water year discharges over a common period of AD 1938–1990.

a geographically consistent relationship between climate in the drainage basins and variability in flow over the common period AD 1938–1990 (Figure 2). Correlations of $r \geq 0.4$ to ≥ 0.6 ($p < 0.05$) between river discharge and PDSI over the basin and adjacent areas are typical. For comparison, *Dai et al.* [2004] reported correlations of $r = 0.69$, 0.61 and 0.19 between annual discharge and basin averaged annual PDSI for the S. Dvina, Lena and Yenisey rivers respectively. The low correlation they reported for the Yenisey may reflect specific opposite trends that occurred in temperature and precipitation in the region during the period of comparison, the sparse distribution of rain gauges and the influence of water withdrawals from the river [*Dai et al.*, 2004]. It is interesting that previous analysis of the relationship between precipitation or precipitation-evaporation (P-E) and discharge of the major Eurasian rivers detected less robust relationships with the possible exception of the Lena Basin [*Serreze et al.*, 2002]. There are many factors that could produce low correlations including the sparse nature of the climatological network and possibilities of errors in the measurements, and the influence of factors beside annual P-E on discharge. The fact that each river appears to have a relatively unique correlation field in terms of PDSI and discharge is consistent with the relatively weak to insignificant correlations between the water year discharge between the six major rivers for the common period AD 1938–1990 (Table 1). Significant correlations typically occur between adjacent basins and are positive, with the exception of the Lena and Kolyma which have a weak but significant negative correlation over the common period.

[11] Although correlations between discharge and PDSI are strongest within each basin and nearby adjacent areas, there is also evidence of wider climatic teleconnections. Discharge from basins as far east as the Lena display positive correlations with PDSI in the Fennoscandian–eastern European region (Figure 2), likely reflecting the persistent importance of moisture transport via the North Atlantic storm track. The Lena discharge also displays relatively high positive correlations with northern and central China, possibly reflecting monsoonal contributions. There is also evidence in the spatial distribution of positive and negative correlations of a bipole in PDSI and discharge in central northern Eurasia. This is clearest when comparing Ob' and Lena PDSI correlation maps (Figure 2). This spatial patterning, with a seesaw between the eastern and western regions, centered generally between the Ob' and Lena

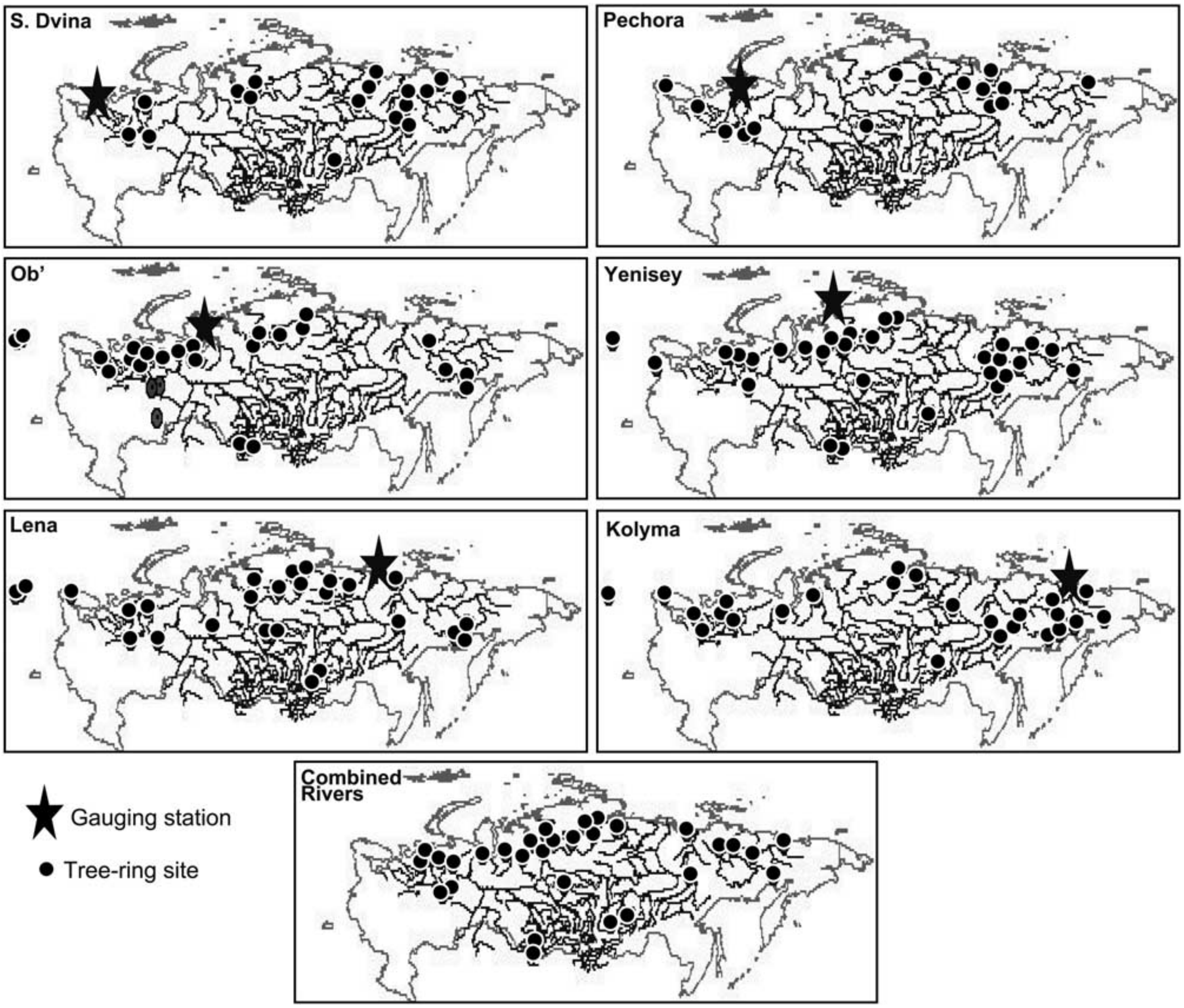

Figure 4. Maps of the locations of the tree ring chronologies (dots) incorporated into each of the annual water year discharge reconstructions. Stars indicate the locations of the gauging stations.

basins, is a well documented feature of Eurasian hydroclimatology [*Fukutomi et al.*, 2003, 2004]. The dipole precipitation pattern is associated with the development of anomalously strong ridge (trough) structures over western and eastern Siberia. The structuring and resulting precipitation dipole may be internally reinforced and maintained by storm track feedbacks related to eddy vorticity fluxes [*Fukutomi et al.*, 2004].

3.2. Dendrohydrological Reconstructions

[12] Dendrohydrological models with the lowest CVSE were selected for each of the major river basins and for the total annual discharge of the combined rivers (Table 2 and Figure 3). All of the models incorporate a number of tree ring sites (16 to 34) distributed across Eurasia (Figure 4), reflecting conditions at sites positively or negatively correlated with the discharge of individual basins. The models explain from 41% (Pechora) to 55% (Yenisey) of the observed variability of flow in the individual basins and 39% of the total combined discharge. The models appear more skillful at capturing the long-term variability in the discharge series, and as is typical in dendrohydrological estimates often underestimate the magnitude of individual peak or low-flow years (Figure 3).

[13] The reconstructed discharge series extend from AD 1800 to 1990 (Figure 5). These reconstructions are available as supporting online material (Table S1 and Data Set S1). Similar to the correlations between gauge records of water year discharge from AD 1938–1990, the correlations between the long-term discharge reconstructions of many of the individual basins are insignificant (Table 3). There is also a significant negative correlation between the discharges of the Lena and Kolyma rivers similar to the observed relationship for AD 1938–1990. These results suggest a reasonable degree of independence in the estimated discharges for each of the rivers. To further examine the veracity of our total discharge reconstruction, we com-

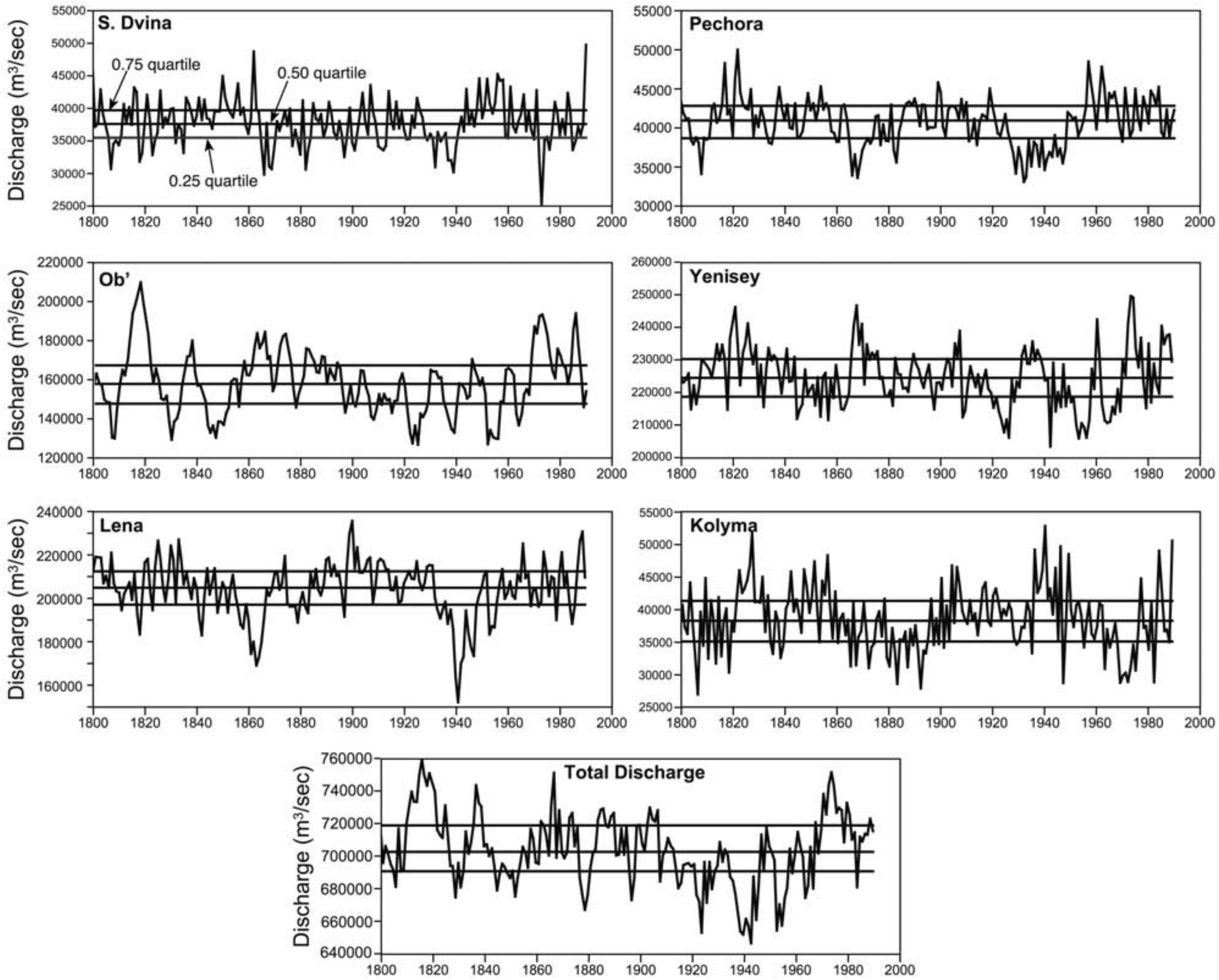

Figure 5. Dendrohydrologically estimated annual water year discharges for the major Eurasian rivers and total combined discharge for the period AD 1800–1990. Horizontal lines are the 0.25, 0.5, and 0.75 quartiles.

pared the estimated time series of combined discharge for all rivers derived from a single dendrohydrological model (Table 2 and Figure 5) with an estimated time series of total discharge derived by summing the annual discharge estimates from the six individual models used to estimate discharge for each river. We found that these two reconstructions of total annual discharge were extremely similar and highly correlated ($r = 0.78$, $p \leq 0.01$).

[14] There is no evidence from the dendrohydrological reconstructions that discharges during the late 20th century are beyond the bounds of natural variability (Figure 5). Although some high-discharge years in the 20th century exceed the 95% confidence limits ($\geq 1.96\ \sigma$) of overall discharge variability from AD 1800 to 1990, similar magnitude events are apparent for the 19th century in all records (Figure 5). The reconstructed means for annual discharge over the period AD 1800–1990 are closely similar to the observed means from the recent period AD 1938–1990 (Table 3). Total discharge for the individual rivers and the combined river discharge show no statistically significant trend over the period AD 1800–1990.

[15] Wavelet analysis shows a peak in significant ($p \leq 0.10$ tested against red noise) variability in the multidecadal band between ~30 and 60 years for the S. Dvina and Pechora, and in the ~60–100-year band for the Lena and Kolyma rivers (Figure 6). The strength of multidecadal variability appears to weaken progressively inland toward the continental interior. However, it should be cautioned that the records are short relative to these low-frequency

Table 3. Correlations Between Dendrohydrological Estimates of Annual Discharge of the Major Northern Eurasian Rivers Over the Common Period AD 1938–1990[a]

	S. Dvina	Pechora	Ob'	Yenisey	Lena
Pechora	**0.390**				
Ob'	**−0.395**	0.019			
Yenisey	−0.316	−0.025	**0.501**		
Lena	0.194	**0.594**	0.104	0.264	
Kolyma	0.090	−0.262	−0.272	−0.173	**−0.494**

[a] Bold values significant at $p \leq 0.05$. The significance values have been calculated to account for the loss of degrees of freedom due to autocorrelation in the time series [*Dawdy and Matalas*, 1964].

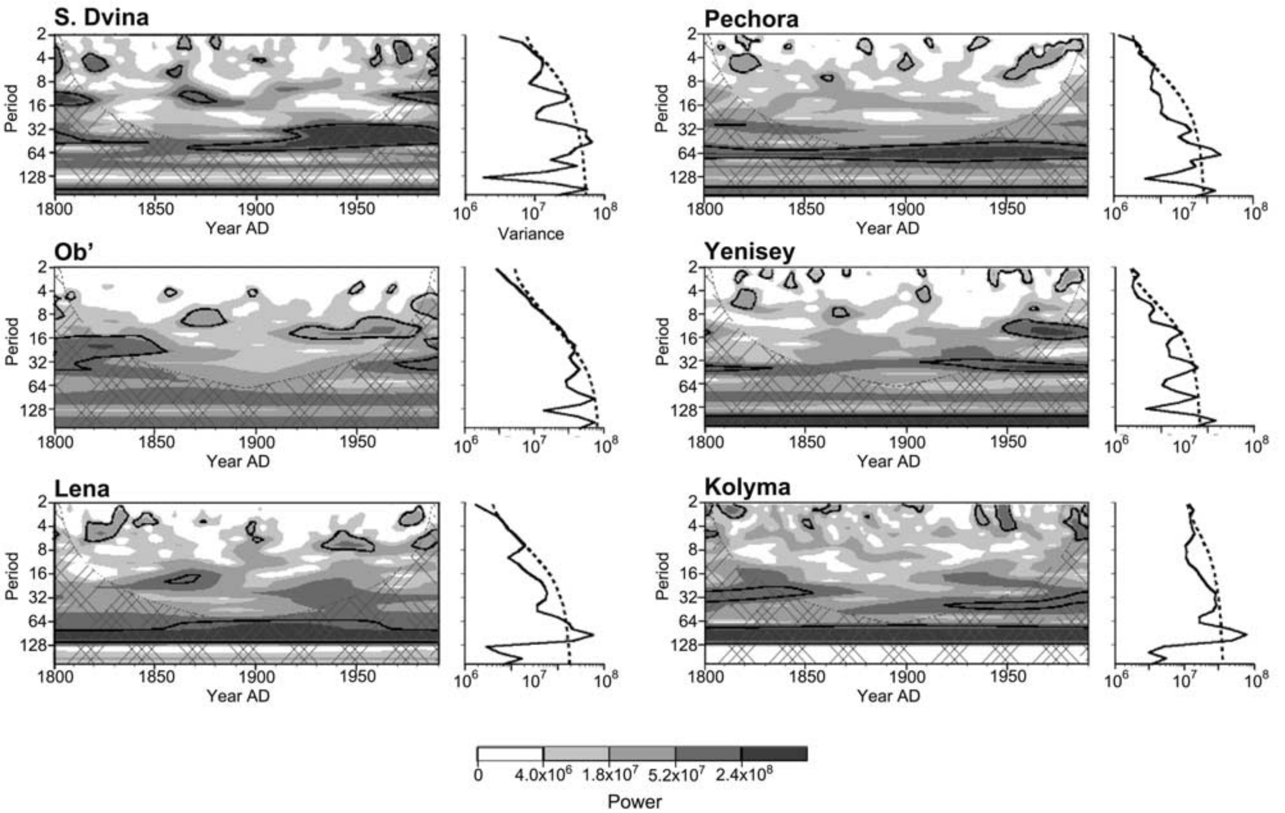

Figure 6. Wavelet power spectrums and global wavelets [*Torrence and Compo*, 1998] for dendrohydrologically estimated discharges for the major northern Eurasian rivers and their total combined discharge for the common period AD 1800–1990. Contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level. Cone of influence is indicated by the cross-hatched region. The 10% significance level is indicated by black outlining on the power spectrums and a dashed line on the global wavelets.

variations, and the lower frequencies fall within the cone of influence of zero padding of the series which can reduce the influence of the signal.

4. Discussion

[16] The correlation analysis highlights the spatial linkages between PDSI and variations in total annual discharge for the major Eurasian rivers over the period AD 1938–1990. These results are consistent with previous analyses that have identified hydroclimatic processes related to moisture transport and evaporation as being key drivers of in recent Eurasian river discharge variability [*Yang et al.*, 2002, 2004; *Peterson et al.*, 2002; *Ye et al.*, 2003, 2004; *Dai et al.*, 2004; *McClelland et al.*, 2004]. The analysis also provides some additional evidence of the spatial patterning of the previously described east-west dipole in annual aridity in central Siberia [*Fukutomi et al.*, 2004]. Most importantly for the present study, as tree ring records are typically sensitive to variations in PDSI, the results of the PDSI-discharge spatial analysis support the applicability of a dendrohydrological network approach to reconstructing discharge.

[17] Assuming that the relationships linking variations in climate to tree growth and to discharge operative over the period AD 1939–1990 have remained generally consistent since AD 1800, the dendrohydrolocal estimates of past flow for the period AD 1800–1990 suggest that the increased annual discharges of the mid to late 20th century [*Peterson et al.*, 2002; *McClelland et al.*, 2004] are not significantly greater than discharges experienced at other times of higher flow over the preceding 200 years, and are thus still within the range of long-term natural variability. However, the present analysis ends in AD 1990 and therefore does not

Table 4. Correlations Between Potential Climatic Forcing Factors and Dendrohydrological Estimates of Annual Discharge of the Major Northern Eurasian Rivers Over the Common Period AD 1800–1975[a]

	Siberia T	AO	NAO
Total	**−0.580**	**−0.321**	0.086
S. Dvina	−0.017	**−0.195**	−0.109
Pechora	−0.104	**−0.342**	−0.004
Ob'	**−0.263**	−0.089	0.103
Yenisey	**−0.180**	−0.091	0.094
Lena	**−0.355**	**−0.339**	0.046
Kolyma	0.088	0.096	−0.011

[a] Bold values significant at $p \leq 0.05$. The significance values have been adjusted to account for the loss of degrees of freedom due to autocorrelation in the time series [*Dawdy and Matalas*, 1964].

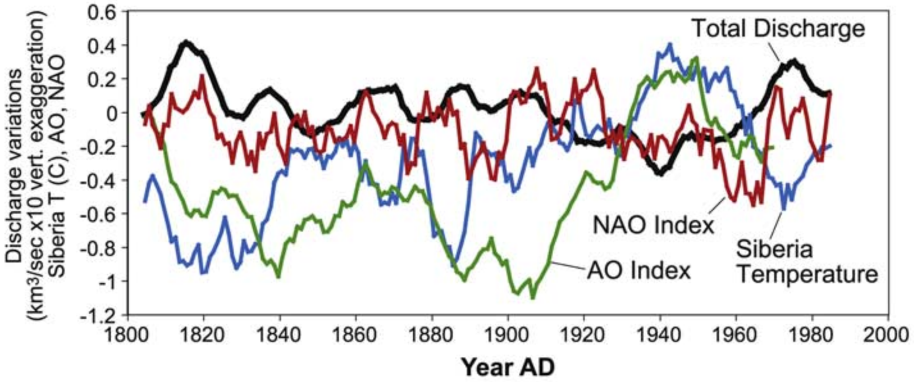

Figure 7. Comparison of smoothed (11-year moving average) total northern Eurasian discharge and reconstructed Siberian temperature deviations (summer), NAO (winter), and AO (summer) from *Briffa et al.* [1995], *Cook et al.* [2002], and *D'Arrigo et al.* [2003], respectively.

address some very recent changes, e.g., increases in low-flow discharge that began in the late 1980s [*Smith et al.*, 2007].

[18] There is considerable evidence in support of increased surface air temperatures (SAT's) in Siberia, the Arctic and the Northern Hemisphere during the 20th century relative to the past 150 to 1000 years [*Briffa et al.*, 1995; *Overpeck et al.*, 1997; *Mann et al.*, 1999; *Jones and Moberg*, 2003; *Moberg et al.*, 2005; *Osborn and Briffa*, 2006; *D'Arrigo et al.*, 2006]. There is also evidence of generally increasing Arctic precipitation over the 20th century [*Kattsov and Walsh*, 2000], often showing good correlations with discharge trends [*Pavelsky and Smith*, 2006]. Given the highly variable nature of the hydroclimatology and annual discharges of these river systems it may be that the magnitudes of any sustained unidirectional changes in moisture balance over the 20th century was not yet sufficient by AD 1990 to produce a long-term trend which is apparent as sustained unprecedented increases in annual discharge. Although there appears to be a strong positive relationship between variations in total discharge from the northern Eurasian rivers and global temperature and the NAO over the past several decades [*Peterson et al.*, 2002], our longer-term discharge records do not indicate a consistent positive significant correlation (Table 4) between discharge, Siberian temperature, the NAO or the AO (Figure 7). Indeed, due largely to the influence of the long-term increases in Siberian temperatures and strength of the summer AO, there are weak negative correlations between discharge on some rivers and these indices over the long common period (AD 1800–1975). These results suggest that some subtle combination of precipitation, evaporation and/or ground thaw and flow conditions may be more important drivers of recently observed discharge variability [*Smith et al.*, 2007]. Finally, it must be cautioned that dendrohydrologic analyses provide reconstructions of variations in climatic conditions that result in changes in river discharge; they might not, for example, capture changes in discharge due to factors such as increased water input due to unprecedented permafrost thaw or fire induced vegetation changes.

[19] The multidecadal variability in the 30–60-year band apparent in the S. Dvina and Pechora records in the far west and the 60–100-year band in and the Lena and Kolyma record to the east may reflect the influence of similar variability detected in North Atlantic and North Pacific SST's and associated climatic indices [*Minobe*, 1999, 2000; *D'Arrigo et al.*, 2003; *MacDonald and Case*, 2005; *Polyakov et al.*, 2005]. Atlantic conditions would be most pervasive for the western basins (S. Dvina and Pechora), while analysis by *Dettinger and Diaz* [2000] indicates that streamflow in the far eastern region is positively correlated with North Pacific SST's. In addition, such long-term variability seems to be a common feature of the northern hemisphere climate system in general [*Mann et al.*, 1995]. Although the genesis of such variability remains poorly understood, it is not surprising to find evidence of low-frequency variation in Eurasian hydroclimatic records. The presence of such natural long-term modes of variability provides further challenges to discerning the influence of recent global warming on northern river discharge.

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References

Aagaard, K., and E. C. Carmack (1989), The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498.

Arnell, N. W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean, *J. Geophys. Res.*, *110*, D07105, doi:10.1029/2004JD005348.

Barber, V. A., G. P. Juday, and B. P. Finney (2000), Reduced growth of Alaska white spruce in the twentieth century from temperature-induced drought stress, *Nature*, *405*, 668–673.

Briffa, K. R., and P. D. Jones (1990), Basic chronology statistics and assessment, in *Methods of Dendrochronology: Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 137–152, Springer, New York.

Briffa, K. R., P. D. Jones, S. G. Shiyatov, F. H. Schweingruber, and E. R. Cook (1995), Unusual twentieth-century summer warmth in a 1000-year temperature record from Siberia, *Nature*, *376*, 156–159.

Broecker, W. S. (1997), Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance?, *Science*, *278*, 1582–1588.

Case, R. A., and G. M. MacDonald (2003), Tree ring reconstructions of streamflow for three Canadian Prairie rivers, *J. Am. Water Resour. Assoc.*, *39*, 703–716.

Cook, E. R., and L. A. Kairiukstis (Eds.) (1990), *Methods of Dendrochronology: Applications in the Environmental Sciences*, 394 pp., Springer, New York.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland (1999), Drought reconstructions for the continental United States, *J. Clim.*, *12*, 1145–1162.

Cook, E. R., R. D. D'Arrigo, and M. E. Mann (2002), A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation Index since A.D. 1400, *J. Clim.*, *15*, 1754–1764.

Curry, R., and C. Mauritzen (2005), Dilution of the northern North Atlantic Ocean in recent decades, *Science*, *308*, 1772–1774.

Curry, R., B. Dickson, and I. Yashayaev (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, *426*, 826–829, doi:10.1038/nature02206.

Dai, A., K. E. Trenberth, and T. Karl (1998), Global variations in droughts and wet spells: 1900–1995, *Geophys. Res. Lett.*, *25*, 3367–3370.

Dai, A., K. E. Trenberth, and T. Qian (2004), A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, *5*, 1117–1130.

D'Arrigo, R. D., E. R. Cook, M. E. Mann, and G. C. Jacoby (2003), Tree-ring reconstructions of temperature and sea-level pressure variability associated with the warm-season Arctic Oscillation since A.D. 1650, *Geophys. Res. Lett.*, *30*(11), 1549, doi:10.1029/2003GL017250.

D'Arrigo, R., R. Wilson, and G. Jacoby (2006), On the long-term context for late twentieth century warming, *J. Geophys. Res.*, *111*, D03103, doi:10.1029/2005JD006352.

Dawdy, D. R., and N. C. Matalas (1964), Statistical and probability analysis of hydrologic data, part III: Analysis of variance, covariance and time series, in *Handbook of Applied Hydrology, A Compendium of Water-Resources Technology*, edited by V. T. Chow, pp. 68–90, McGraw-Hill, New York.

Dettinger, M. D., and H. F. Diaz (2000), Global characteristics of streamflow seasonality and variability, *J. Hydrometeorol.*, *1*, 289–310.

Drobyshev, I., and M. Niklasson (2004), Linking tree rings, summer aridity, and regional fire data: An example from the boreal forests of the Komi Republic, East European Russia, *Can. J. For. Res.*, *34*, 2327–2339.

Fukutomi, Y., H. Igarashi, K. Masuda, and T. Yasunari (2003), Interannual variability of summer water balance components in three major river basins of northern Eurasia, *J. Hydrometeorol.*, *4*, 283–296.

Fukutomi, Y., K. Masuda, and T. Yasunari (2004), Role of storm track activity in the interannual seesaw of summer precipitation over northern Eurasia, *J. Geophys. Res.*, *109*, D02109, doi:10.1029/2003JD003912.

Garen, D. C. (1992), Improved techniques in regression-based streamflow volume forecasting, *J. Water Resour. Plann. Manage.*, *118*, 654–670.

Gedney, N., P. M. Cox, R. A. Betts, O. Boucher, C. Huntingford, and P. A. Scott (2006), Detection of a direct carbon dioxide effect in continental river runoff records, *Nature*, *439*, 838–841, doi:10.1038/nature04504.

Hidalgo, H. G., T. C. Piechota, and J. A. Dracup (2000), alternative principal components regression procedures for dendrohydrologic reconstructions, *Water Resour. Res.*, *36*, 3241–3249.

Jones, P. D., and A. Moberg (2003), Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001, *J. Clim.*, *16*, 206–223.

Kattsov, V. M., and J. E. Walsh (2000), Twentieth-century trends of Arctic precipitation from observational data and a climate model simulation, *J. Clim.*, *13*, 1362–1370.

Larsen, C. P. S., and G. M. MacDonald (1995), Relations between tree ring widths, climate and annual area burned in the boreal forest of Alberta, *Can. J. For. Res.*, *25*, 1746–1755.

MacDonald, G. M., and R. A. Case (2005), Variations in the Pacific Decadal Oscillation over the past millennium, *Geophys. Res. Lett.*, *32*, L08703, doi10.1029/2005GL022478.

Manabe, S., and R. J. Stouffer (1994), Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide, *J. Clim.*, *7*, 5–23.

Mann, M. E., J. Park, and R. S. Bradley (1995), Global interdecadal and century scale climate oscillations during the past five centuries, *Nature*, *378*, 266–270.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1999), Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett.*, *26*, 759–762.

McClelland, J. W., R. M. Holmes, B. J. Peterson, and M. Stieglitz (2004), Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change, *J. Geophys. Res.*, *109*, D18102, doi:10.1029/2004JD004583.

Minobe, S. (1999), Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts, *Geophys. Res. Lett.*, *26*, 855–858.

Minobe, S. (2000), Spatio-temporal structure of the pentadecadal variability over the North Pacific, *Prog. Oceanogr.*, *47*, 381–408.

Moberg, A., D. M. Sonechkin, K. Holmgren, N. M. Datsenko, and W. Karlén (2005), Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, *Nature*, *443*, 613–617.

Ogi, M., Y. Tachibana, and K. Yamazaki (2003), Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation, *Geophys. Res. Lett.*, *30*(13), 1704, doi:10.1029/2003GL017280.

Osborn, T. J., and K. R. Briffa (2006), The spatial extent of 20th century warmth in the context of the last 1200 years, *Science*, *311*, 841–844.

Osborn, T. J., K. R. Briffa, and P. D. Jones (1997), Adjusting variance for sample-size in tree-ring chronologies and other regional-mean time series, *Dendrochronologia*, *15*, 89–99.

Overpeck, J., et al. (1997), Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256.

Palmer, W. C. (1965), Meteorological drought, *Res. Paper no.*45, 58 pp., Dept. of Commerce, Washington, D.C.

Pavelsky, T. M., and L. C. Smith (2006), Intercomparison of four global precipitation datasets and their correlation with increased Eurasian river discharge to the Arctic Ocean, *J. Geophys. Res.*, *111*, D21112, doi:10.1029/2006JD007230.

Pederson, N., G. C. Jacoby, R. D'Arrigo, B. Buckley, C. Dugarjav, and R. Mijiddorj (2001), Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: AD 1651–1995, *J. Clim.*, *14*, 872–881.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.

Polyakov, I. V., U. Bhatt, H. Simmons, D. Walsh, J. Walsh, and X. Zhang (2005), Multidecadal variability of North Atlantic temperature and salinity during the Twentieth Century, *J. Clim.*, *18*, 4562–4581.

Rahmstorf, S. (2002), Oceanic circulation and climate during the past 120,000 years, *Nature*, *419*, 207–214.

Serreze, M. C., and A. J. Etringer (2003), Precipitation characteristics of the Eurasian Arctic drainage system, *Int. J. Climatol.*, *23*, 1267–1291.

Serreze, M. C., D. H. Bromwich, M. P. Clark, A. J. Etringer, T. Zhang, and R. Lammers (2002), Large-scale hydro-climatology of the terrestrial Arctic drainage system, *J. Geophys. Res.*, 107, 8160, doi:10.1029/2001JD000919, [printed *108*(D2), 2003].

Smith, L. C., T. M. Pavelsky, G. M. MacDonald, A. I. Shiklomanov, and R. Lammers (2007), Rising minimum flows in northern Eurasian rivers suggest a growing influence of groundwater in the high-latitude water cycle, *J. Geophys. Res.*, doi:10.1029/2006JG000327, in press.

Stockton, C. W., and H. C. Fritts (1973), Long-term reconstruction of water level changes for Lake Athabasca by analysis of tree rings, *Water Resour. Bull.*, *9*, 1006–1027.

Szeicz, J. M., and G. M. MacDonald (1996), A 930-year ring-width chronology from moisture sensitive white spruce (Picea glauca Moench) from northwestern Canada, *Holocene*, *6*, 345–351.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.

Vellinga, M., and R. A. Wood (2002), Global climatic impacts of a collapse of the Atlantic thermohaline circulation, *Clim. Change*, *43*, 251–267.

Vörösmarty, C. J., L. D. Hinzman, B. J. Peterson, D. H. Bromwich, L. C. Hamilton, J. Morison, V. E. Romanovsky, M. Sturm, and R. S. Webb (2001), *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study*, 84 pp., Arctic Res. Consortium of the U.S., Fairbanks, Alaska. (Available at http://arcticchamp.sr.unh.edu/report.shtml.)

Yang, D., B. Goodison, J. Metcalf, P. Louie, E. Elomaa, C. Hanson, V. Golubev, T. Gunther, J. Milkovic, and M. Lapin (2001), Compatibility evaluation of national precipitation gauge measurements, *J. Geophys. Res.*, *106*, 1481–1491.

Yang, D., D. L. Kane, L. D. Hinzman, X. Zhang, T. Zhang, and H. Ye (2002), Siberian Lena River hydrologic regime and recent change, *J. Geophys. Res.*, *107*(D23), 4694, doi:10.1029/2002JD002542.

Yang, D., B. Ye, and A. Shiklomanov (2004), Discharge characteristics and changes over the Ob River watershed in Siberia, *J. Hydrometeorol.*, *5*, 595–610.

Ye, B., D. Yang, and D. L. Kane (2003), Changes in Lena River streamflow hydrology: Human impacts versus natural variations, *Water Resour. Res.*, *39*(7), 1200, doi:10.1029/2003WR001991.

Ye, H., D. Yang, T. Zhang, X. Zhang, S. LaDochy, and M. Ellison (2004), The impact of climatic conditions on seasonal river discharges in Siberia, *J. Hydrometeorol.*, *5*, 286–295.

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