The Impact of Climatic Conditions on Seasonal River Discharges in Siberia

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ABSTRACT

The influences of surface climate conditions and atmospheric circulation on seasonal river discharges of the Ob, Yenisei, and Lena River basins during 1936–95 have been examined and quantified. Climatic variables include seasonal basin-averaged surface air temperatures, precipitation, maximum snow accumulation depth, and starting and ending dates of the basins' continuous snow cover. Atmospheric circulation is represented by the Northern Hemisphere annular mode (NAM) index. The combinations of these climatic and atmospheric variables explain about 31% to 55% of the variance of the annual total discharges of these rivers. On average, climatic and atmospheric variables explain 35% to 69% variance of spring discharges, 34% to 47% variance of summer discharges, 21% to 50% variance of fall discharges, and 18% to 36% variance of winter discharges. This study reveals that the spring thermal condition is most significant for spring discharge and negatively affects summer discharge. Climatic conditions during the previous winter through fall influence fall discharges, while the atmospheric conditions of the previous summer and fall affect winter discharges. Also, winter snow accumulation influences summer and fall discharges of the Ob and Yenisei Rivers but affects winter and spring discharges of the Lena River, suggesting the importance of topography and permafrost conditions to river discharges over high-latitude regions.

1. Introduction

Three major rivers in Siberia, Russia—the Ob, Yenisei, and Lena—together contribute more than 45% of the total freshwater inflow to the Arctic Ocean (Shiklomanov et al. 2000; Prowse and Flegg 2000). The variability of these rivers' discharges significantly affects salinity and sea ice formation and hence global ocean circulation and climate (Aagaard and Carmack 1989). The dynamics of discharge also control the timing and magnitude of flooding and sediment distribution over the basins themselves (Burn 1997; Cunderlik and Burn 2002; Smith and Alsdorf 1998). Changes in the discharge of these rivers possibly associated with climate warming in high latitudes have been recognized by recent studies (Georgievskii et al. 1996; Grab et al. 2000; Peterson et al. 2002; Serreze et al. 2000, 2002; Shiklomanov et al. 2000; Yang et al. 2002). In particular, most of these studies focused on trends of river discharges and shifts in peak flow times. For example, Peterson et al. (2002) suggested that increased Arctic river discharges are correlated with the increasing trends in the North Atlantic Oscillation (NAO) and global surface air temperatures through enhanced moisture transport into the Arctic. The observed earlier snowmelt and shift of peak flow a few days earlier is a response to increasing spring air temperature (Yang et al. 2002). This directly affects flooding intensity and frequency in the region (Burn 1997; Cunderlik and Burn 2002).

River discharge is an integrative result of water balance in the basin. Many factors influence this water cycle simultaneously and at different time scales. In addition, the interactions among these affecting factors are complex and have not been fully understood for the Arctic. Widely available information describing the state of the atmosphere over the Arctic region includes atmospheric circulation, surface climatic variables such as air temperature and precipitation, snow cover and depth, and timing of snow cover.

Atmospheric circulation has a significant influence on the Arctic hydrological system (Fukutomi et al. 2003; Proshutinksy et al. 1999; Walsh 2000; Semiletov et al. 2000). The major atmospheric circulation pattern over the Arctic region is the Arctic Oscillation (AO) or more precisely, the Northern Hemisphere annular mode (NAM; Thompson and Wallace 2000). The NAM de-

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scribes atmospheric activity centered over the eastern side of the Arctic Ocean near Siberia (Thompson and Wallace 1998, 2000). Arctic surface air pressure has been decreasing (Walsh et al. 1996), and thus the related NAM index value shows a positive trend during the last few decades (Thompson et al. 2000). It has also been suggested that the positive trend in the NAM index is partially responsible for increasing cold-season surface air temperatures in high-latitude land areas (Thompson and Wallace 1998). Surface air temperature directly affects snowmelt rate and the timing of the melt season as well as evapotranspiration in warm seasons and thus is another important factor affecting seasonal river discharge.

Winter precipitation and snow depth over Siberia have experienced large interannual and decadal variations in addition to positive trends during the past six to seven decades (Ye 2001a,b; Ye et al. 1998). A large portion of winter precipitation accumulates as snow and contributes to warm-season river discharges. Thus, winter precipitation and snow-cover extent exerts a certain control on the seasonal distribution of river discharges (Yang et al. 2003). Since most of these atmospheric and climatic variables are interrelated to a certain extent, the relative importance of the key climatic variables that control seasonal river discharge and the overall magnitude of these influences are not very clear.

The goal of this study is to quantify the extent of the controls of atmosphere and climatic conditions over river discharge variability at seasonal and interannual time scales by identifying and assessing the critical climatic variables or combinations thereof that are significantly associated with river discharges in the three major Siberian river basins. We will examine all available records of atmosphere circulation and climate conditions that may influence hydrology.

2. Datasets and methods of analysis

a. Data sources

Monthly river discharges during 1936–95 at three basin outlet stations, Salekhard on the Ob, Igarks on the Yenisei, and Kusur on the Lena, are used in this study. The data are from R-ArcticNET, originally collected and quality controlled by the Russian Hydrometeorological Services (Lammers et al. 2001). The discharge at each of these gauge stations is used to represent that river's basin-scale values. Seasonal values are the total of the three monthly values in the standard four seasons.

Maximum snow depths are derived from the Historical Soviet Daily Snow Depth CD-ROM, version 2.0, available from the National Snow and Ice Data Center (NSIDC), Boulder, Colorado (Armstrong 2001). This dataset consists of daily snow depth observations averaged from three measuring rods surrounding each station. The highest snow depth value during a continuous snow-cover period is selected as the maximum snow depth for each year. The 86 stations located on or near the three river basins that have no more than five missing years during 1936–95 are selected for this study (Fig. 1).

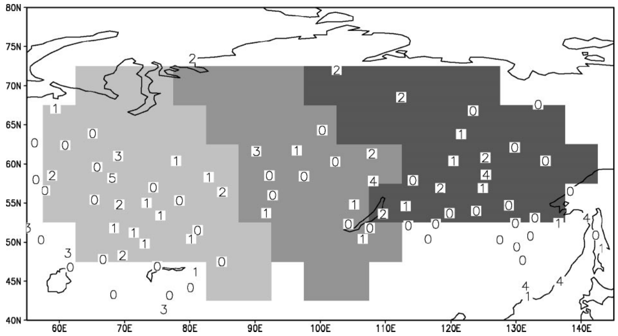

FIG. 1. Station distribution of maximum snow accumulation. The numbers indicate the number of missing years during 1936–95. Three-stage shading indicates the three rivers' drainage basins from left to right: Ob River (light shade), Yenisei River (moderate shade), and Lena River (dark shade).

The first and the last dates of continuous snow cover are also derived from daily snow records from the NSIDC CD-ROM. They are the beginning and ending dates of the longest continuous snow-cover period in the middle of winter. The dates are then converted to Julian dates. Details of this dataset are described in Ye and Ellison (2003).

Both maximum snow depth and first and last date of continuous snow cover are interpreted into grid values of 5° latitude × 5° longitude using Shepard's local-search interpolation on a spherical surface (Willmott et al. 1985). Then, the time series of the basin-averaged values for each of these snow variables is derived for the three basins from grid values within the corresponding basin. Since each river basin covers a large geographic area and few stations are located north of 60°N, the basin-averaged snow condition may not necessarily represent the real basin condition accurately. However, the interannual variation should be a good indicator for basinwide thermal and moisture anomalies during winter and spring. Lacking observations in the northernmost areas of high-latitude regions is also a common problem for other climatic variables such as air temperature and precipitation. Still, the basin averages are valuable for temporal variability (Yang et al. 2002).

Surface air temperature and precipitation data are from the Jones (1994) and Hulme (1991) gridded 5° latitude × 5° longitude grids. Seasonal averages are derived from monthly values; basin-averaged seasonal air temperature and precipitation are derived from averaging the grid values within each basin.

D. Thompson's monthly AO index beginning in 1899 is available from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington. Each of the values is the projection of the leading empirical orthogonal function (EOF) of sea level pressure (SLP) polarward of 20°N, based on all months between January 1955 and April 1999, onto SLP anomalies back to January 1899 (Thompson and Wallace 2000). The time period of 1936–95 is used in this study; seasonal index values are averaged from the monthly values.

b. Methods of analysis

To examine the linear associations between climatic or atmospheric circulation variables and seasonal river discharges, Pearson's correlation analysis is used. In the correlation analysis, seasonal lag correlations between climatic or atmospheric variables and river discharge is also included to examine the possible effects of seasonal and regional variations in ground water storage and the lags between snowmelt and rainfall–flood processes due to basin integration. The correlation coefficients computed for each basin separately will also enable us to reveal the differences in the hydrological responses to the same atmospheric/climatic conditions by the basin.

Stepwise regression analysis is used to identify the most significant variables contributing to seasonal and annual discharge variability. Since the climatic variables and the NAM are highly colinear, prior to the regression analysis, factor analysis (R mode) is applied to all seasonal atmospheric and climatic variables to reduce the number of variables and resulting in a few major independent factors that explain the large variability of the original variables in each basin. The resulting factors are independent of each other and thus the outputs from regression analysis are more accurately representative of the true variance explained by the combined effects of the atmosphere and climate.

The factors whose eigenvalues are larger than 1 are retained for rotation (Varimax with Kaiser normalization) to find better variables that adequately and clearly describe the original variables (Shaw and Wheeler 1997). Each factor will be given a new variable name based on its high correlation coefficients to original climatic variables. Thus, the factors selected by stepwise regression analysis will reveal the significant contributing combined atmospheric/climatic conditions that affect the river discharges.

Factor analysis resulted in six factors in each river basin explaining 69.70%, 71.28%, and 72.76% of total variance of the original atmospheric and climatic variables for the Ob, Yenisei, and Lena river basins respectively (Table 1). Because of different climate and atmospheric mechanisms in the three basins, not all new factors are identical among these basins. The first factor is spring warmth, highly correlated with spring air temperature and snow ending dates in all three river basins. The second factor is summer environment for the Ob River and winter environment for both the Yenisei and Lena Rivers. The environment factor is a combination of air temperature and precipitation. The third factor is fall circulation and heat related to fall air temperature

TABLE 1. New variables (factors) resulting from factor analyses and their correlation with original climatic variables.

	Ob		Yenisei		Lena	
Factors	New variable name (% of variance)	Climatic variable (correlation coef)	New variable name (% of variance)	Climatic variable (correlation coef)	New variable name (% of variance)	Climatic variable (correlation coef)
F1	Spring warmth (18.54%)	Spring air temp (−0.452) Snow end date (0.419)	Spring warmth (22.10%)	Spring air temperature (0.330) Snow end date (−0.325)	Spring warmth (22.13%)	Spring air temperature (0.357) Snow end date (−0.330)
F2	Summer environment (13.54%)	Summer precipitation (−0.482) Summer air temp (0.457)	Winter environment (13.2%)	Winter precipitation (0.432) Winter air temperature (0.349)	Winter environment (12.81%)	Winter precipitation (0.399) Winter air temperature (0.388)
F3	Fall circulation and heat (12.37%)	Fall AO index (0.419) Fall air temp (0.385)	Fall circulation and heat (12.03%)	Fall air temperature (0.433) Fall AO index (0.372)	Fall circulation and heat (11.33%)	Fall AO index (0.454) Fall air temperature (0.415)
F4	Winter moisture (10.47%)	Snow depth (0.509) Winter precipitation (0.472)	Summer circulation (9.20%)	Summer AO index (0.687)	Fall moisture and summer heat (9.63%)	Fall precipitation (−0.534) Summer air temperature (0.420) Summer AO index (0.408)
F5	Winter and summer circulation (7.75%)	Summer AO index (0.528) Winter AO index (0.420)	Summer and fall moisture (7.78%)	Summer precipitation (0.597) Fall precipitation (−0.460)	Summer moisture (8.89%)	Summer precipitation (0.617)
F6	Spring and fall moisture (7.0%)	Fall precipitation (0.600) Spring precipitation (0.435)	Summer heat and spring moisture (6.97%)	Summer air temperature (0.729) Spring precipitation (−0.510)	Snow cover (7.97%)	Snow depth (0.626) Snow start date (−0.474)

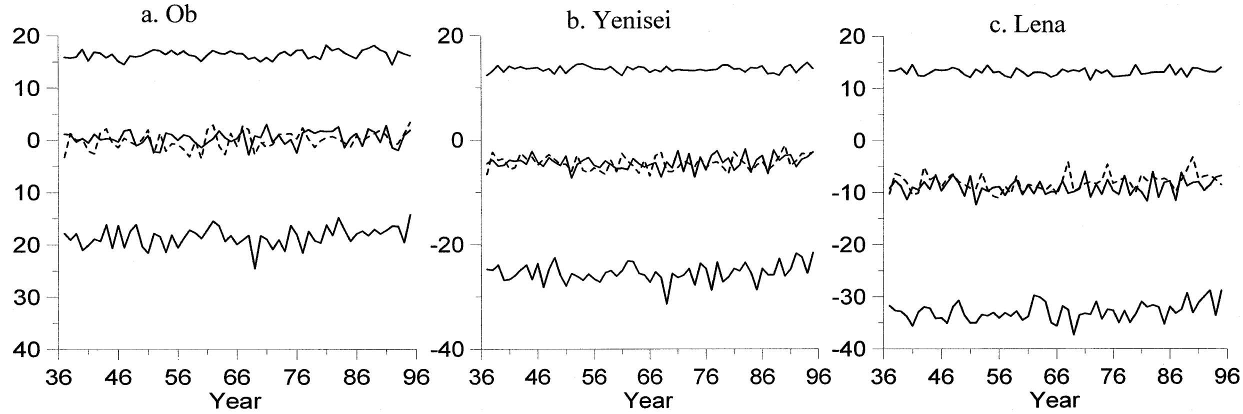

FIG. 2. Time series of seasonal air temperatures at the three river basins. The upper solid line is summer, middle dashed line is spring, middle solid line is fall, and bottom solid line is winter basin-averaged surface air temperature. The y axis is (°C).

and AO index. The fourth factor is winter moisture for the Ob, summer circulation for the Yenisei, and fall moisture and summer heat for the Lena. The fifth factor is winter and summer circulation, summer and fall moisture, and summer moisture for the Ob, Yenisei, and Lena Rivers, respectively. The sixth factor is spring and fall moisture, summer heat and spring moisture, and snow cover for the three rivers, respectively.

3. Results

a. Basin-scale trends in climatic and atmospheric variables

Statistically significant (at a 0.05 level) increasing winter and spring air temperatures are found in all three drainage basins during the study period of 1936–95 (Fig. 2). Increasing winter precipitation occurred over the Ob and decreasing summer precipitation over the Yenisei River basin (Fig. 3). The value of the AO index has also increased, suggesting a decreasing SLP in the Arctic Ocean during the last 60 yr of the study time period.

Maximum snow depth showed a statistically significant increasing trend in the Ob and Lena River basins at or higher than a 0.05 level (Fig. 4). It is also noticeable that the increasing trend started around 1976 in the Ob River. Maximum snow depth over the Yenisei basin first decreased until the early 1970s and then increased during the last 30 yr.

There is no significant trend of starting or ending snow dates over these three drainage basins during the study time period (Fig. 5). The snow ending date is affected both by spring air temperature and maximum snow depth, which both showed positive trends. Higher spring air temperatures result in an earlier snow-cover ending date, while higher snow depth is likely to delay the snow-cover ending date; thus, their effects on snow ending date seem to cancel each other out.

Time series of river discharges in four seasons are shown in Fig. 6. Winter has the smallest and summer has the largest discharge for all three rivers. Discharge in the fall is slightly higher than in spring. Significant increasing trends are found in winter discharges of all three rivers. Spring discharge also shows a statistically significant increasing trend ($p < 0.05$) in the Lena River. No trends are found for summer and fall discharges.

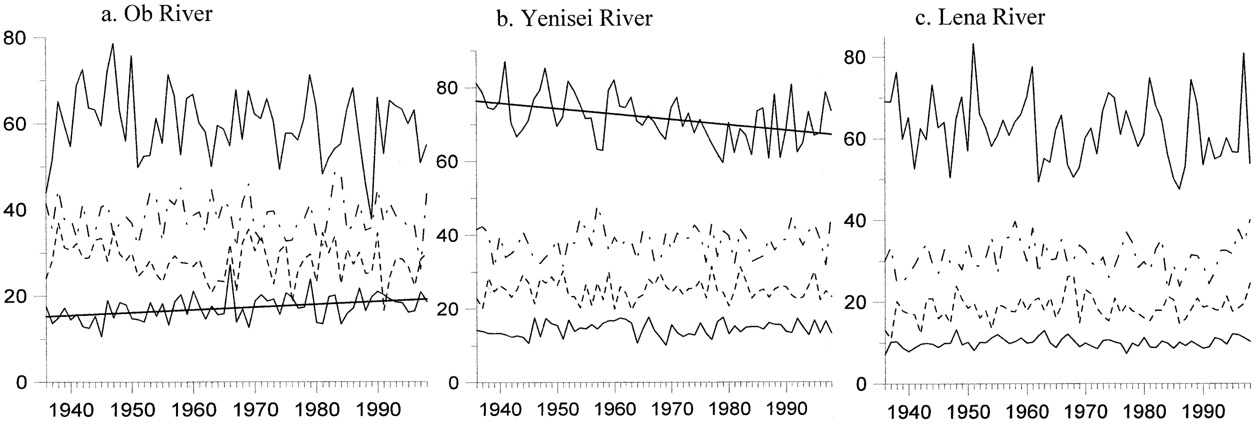

FIG. 3. Time series of seasonal precipitation at the three river basins. The top and bottom solid lines are the summer and winter precipitation, dashed lines are spring precipitation, and combined dashed and dotted lines are fall precipitation. The y axis is precipitation (mm).

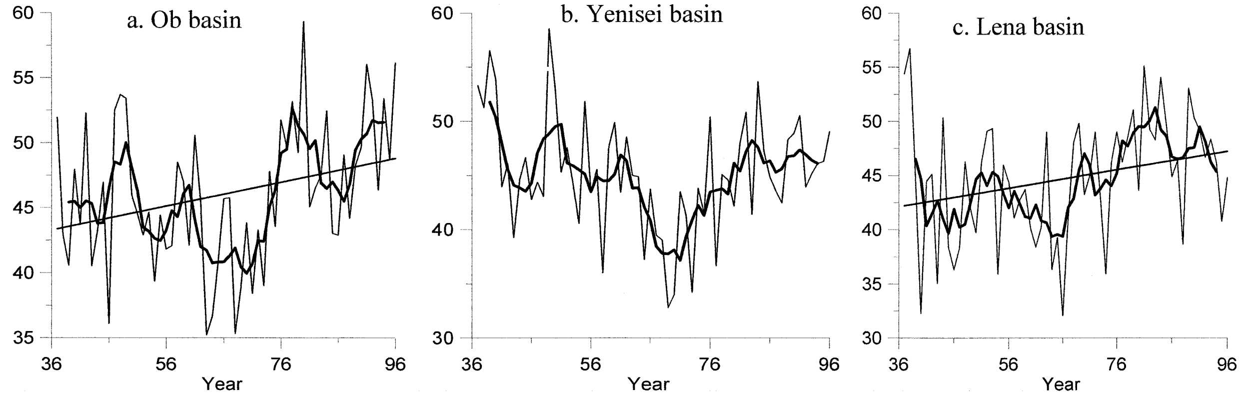

FIG. 4. Time series of maximum snow depth for the three basins. Straight lines are the linear trends significant at a 0.05 level. Thick smoothed lines are 5-yr moving averages. The *y* axis is snow depth (cm).

b. Correlation results

Spring river discharges are positively correlated with spring air temperature and negatively correlated with snow ending dates for all three rivers. Also, spring discharge is correlated with winter and spring AO index, which is likely related to spring air temperature since AO indices are also closely correlated with spring air temperatures.

Unlike spring discharges, summer discharges are positively correlated with snow-cover ending date and negatively correlated with spring air temperature. Earlier snow melting in spring may have resulted in less water for summer discharge. Maximum snow depth and winter precipitation are positively correlated with summer discharge in the Ob and Yenisei river basins. This suggests that melting water from snow is able to influence summer discharge in the Ob and Yenisei river basins. Greater maximum snow depth (and/or winter precipitation) will likely increase the length of snowmelting time, resulting in more water being carried over to summer, and thus greater summer discharge. This can also be seen from the high correlation between snow ending date and summer discharge. Summer air temperature is negatively correlated with summer discharge in the Ob and Lena river basins, suggesting that higher summer air temperature increases evapotranspiration and reduces summer runoff. The negative correlation between spring AO index and summer discharge probably results from the influence of AO on spring air temperatures.

Maximum snow depth, snow ending date, spring air temperature, summer air temperature, spring precipitation, and summer precipitation are correlated with fall discharge in the Ob River basin in a way very similar to that of summer discharge. This suggests that the influences of these variables are persistent through summer to the fall season's discharge. It may also explain the high correlation between summer and fall discharge in the Ob River basin. In the Yenisei River basin, fall discharge is positively correlated with maximum snow depth and summer precipitation, suggesting that both summer precipitation and snow contribute to fall discharge. In the Lena River basin, fall discharge is also positively correlated with summer precipitation and winter AO index but is not correlated with snow depth. In all three rivers, fall discharge is most significantly correlated with summer precipitation.

Climate in the winter season is expected to have little influence on winter discharge. One of the major reasons is that extremely low air temperatures and precipitation accumulate as snow and contribute little to winter dis-

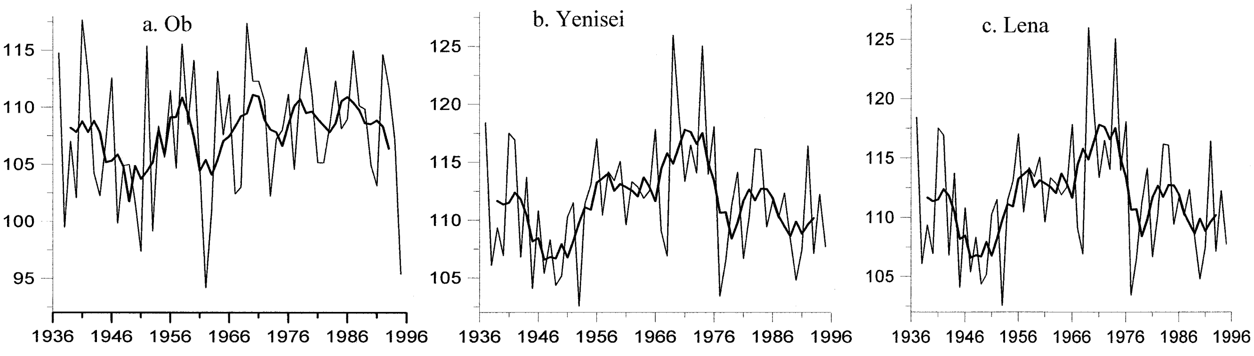

FIG. 5. Time series of the ending dates of the continuous snow cover at the three Siberian river basins. Smoothed solid lines are the 5-yr running averages. The *y* axis represents Julian days.

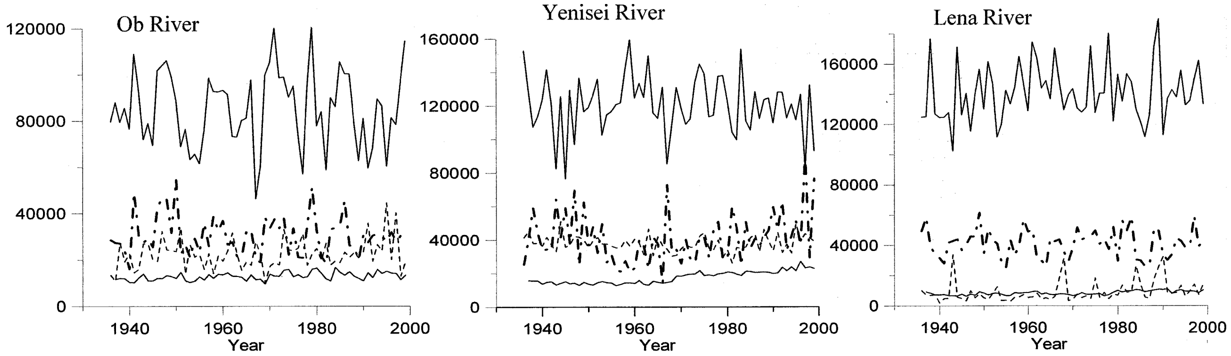

FIG. 6. Time series of seasonal discharges for the three basins. Top and bottom solid lines are summer and winter discharge, respectively. The dashed line is spring discharge, and the combined dashed and dotted line (thicker) is fall discharge. The y axis is $m^3 s^{-1}$.

charge. Most discharge water from the winter season is from base flow (from the subsurface) continued from fall discharges. This can be reflected in a very high correlation between winter discharge and December (even November) discharge in these three drainage basins. Thus, the climatic variables correlated with winter discharge originated in the previous seasons (summer and fall). For example, winter discharge is negatively correlated with previous summer air temperature and positively correlated with previous snow maximum, summer precipitation, and fall precipitation in the Ob River basin. It is worth noting that winter climate conditions (temperature, circulation, and maximum snow) influence winter discharge only in the Lena River basin. One possible explanation for this is the more extensive permafrost in the Lena River basin. Approximately 78%–93% of the Lena River basin is occupied by continuous permafrost (Brown et al. 1998; Zhang et al. 1999, 2000; Serreze et al. 2003). Permafrost distribution in the Yenisei River basin is more discontinuous and sporadic (36%–55%) than in the Lena River basin. Only 4%–10% of the Ob River basin is underlain with permafrost. A warmer winter climate delays active-layer freeze-up over permafrost, thus increasing winter discharge. Also, snow acts as an insulation layer; the thicker snow results in warmer ground and a later freeze date of the active layer and thus higher discharge in winter. The connection between winter AO and winter discharge in the Lena River basin is probably related to air temperature since AO and winter air temperature are highly correlated with each other.

c. *Stepwise regression results*

Stepwise regression results for seasonal and annual discharges are listed in Table 2. As expected, spring warmth is a significant contributor to spring discharge in all three rivers, explaining about 55%, 35%, and 39% variance of spring discharges for the Ob, Yenisei, and Lena Rivers, respectively. Snow cover shows up as an important contributor to spring discharge in the Ob and Lena river basins also. Winter environment and spring and fall moisture also contribute to spring discharges in the Lena and Ob Rivers, respectively. These are consistent with the results of correlation analysis. These factors explain about 69%, 35%, and 57% of the total variance of spring discharges for the Ob, Yenisei, and Lena river basins, respectively.

Spring warmth and winter environment (or winter moisture) are important factors for summer discharge in all three rivers. Summer environment (or summer moisture) affects summer discharge in the Ob and Lena Rivers. Spring and fall moisture and fall moisture and summer heat also contribute to the variability of summer discharges in the Ob and Lena river basins. The total variances explained for summer discharge are about 47%, 34%, and 34% in the Ob, Yenisei, and Lena river basins, respectively.

Summer moisture (or summer environment) is an important contributor to fall discharges in all three rivers, although it explains much less variance in the Yenisei River (5% versus 36% and 36% for the Ob and Lena Rivers, respectively). Winter moisture (or winter environment) is an important contributor to fall discharge in the Ob and Yenisei river basins. Also, spring warmth affects the Ob and fall heat affects the Yenisei discharges in the fall. Total variances explained for fall discharge are 50%, 22%, and 36% for the Ob, Yenisei, and Lena river basins, respectively.

Fall moisture combined with spring moisture, summer moisture, and summer heat contributes to winter discharges in the Ob, Yenisei, and Lena river basins, respectively. Winter moisture contributes to the Ob River winter discharge, and snow contributes to the Lena River winter discharge. Summer circulation affects Yenisei winter discharge, and winter environment affects Lena winter discharge. Together, these factors explain about 18%, 36%, and 20% of winter discharges for the Ob, Yenisei, and Lena river basins, respectively.

For annual discharge totals, stepwise regression shows that the climate in each of the four seasons exerts certain influences on the annual total discharge. In the Ob River basin, a total of 48% of annual discharge is explained by summer environment, winter moisture,

TABLE 2. Regression results of discharges (dependent variables) and new variables (independent variables significant at above 0.15).

Ob			Yenisei			Lena		
Variables selected	Std regular coef	Tot explained variance	Variables selected	Std regular coef	Tot explained variance	Variables selected	Std regular coef	Tot explained variance
			Spring season					
Spring warmth	0.739^{a}	68.72%	Spring warmth	0.595^{a}	35.42%	Spring warmth	0.626^{a}	56.74%
Spring and fall heat	−0.324^{a}					Snow cover	0.360^{a}	
Winter moisture	0.191^{b}					Winter environment	0.214^{b}	
			Summer season					
Summer environment	−0.400^{b}	47.13%	Spring warmth	−0.499^{a}	33.96%	Summer moisture	−0.499^{a}	34.23%
Spring warmth	−0.364^{b}		Winter environment	0.301^{b}		Winter environment	0.285^{b}	
Winter moisture	0.318^{b}					Fall moisture and summer heat	−0.208^{c}	
Winter and summer circulation	−0.232^{c}					Spring warmth	−0.191	
Spring and fall moisture	0.155							
			Fall season					
Summer environment	−0.604^{a}	50.04%	Fall circulation and heat	0.298^{c}	20.67%	Summer moisture	0.601^{a}	36.07%
Winter moisture	0.280^{b}		Winter environment	0.252^{c}				
Spring warmth	−0.239^{b}		Summer and fall moisture	0.234				
			Winter season					
Spring and fall moisture	−0.341^{b}	18.41%	Summer and fall moisture	−0.407^{a}	35.64%	Snow cover	0.281^{c}	20.06%
Winter moisture	0.260^{c}		Summer circulation	0.301^{b}		Fall moisture and summer heat	0.248^{c}	
						Winter environment	0.245^{c}	
			Annual total					
Summer environment	−0.501^{a}	48.23%	Winter environment	0.355^{b}	30.92%	Summer moisture	0.553^{a}	54.60%
Winter moisture	0.411^{a}		Fall circulation and heat	0.287^{b}		Winter environment	0.361^{a}	
Winter and summer circulation	−0.200^{c}		Summer heat and spring moisture	−0.233^{c}		Snow cover	0.262^{b}	
Spring warmth	−0.152		Summer circulation	0.215		Fall moisture and summer heat	−0.204	

[a] Significant at above 0.001.
[b] Significant at above 0.01.
[c] Significant at above 0.05.

winter and summer circulation, and spring warmth. In the Yenisei River basin, winter environment, fall heat, summer heat and spring moisture, and summer circulation affect annual discharge. In the Lena River basin, summer moisture, winter environment, snow cover, and fall moisture and summer heat affect annual discharge. These factors explain a total of about 48%, 31%, and 55% of the annual discharge totals for the Ob, Yenisei, and Lena Rivers, respectively.

4. Summary and discussion

The associations between seasonal discharges and climatic and atmospheric variables have been evaluated using correlation and regression analyses for the three river basins of the Ob, Yenisei, and Lena Rivers during 1936–95.

The generally consistent correlation results among the three rivers include the following: 1) spring discharges are highly affected by spring thermal conditions reflected in air temperature and the last date of continuous snow cover. 2) Summer discharges are negatively correlated with spring thermal conditions. Depending on the river basins, precipitation from winter to summer has certain influences on summer discharges. 3) Fall discharges are closely associated with summer moisture conditions. 4) Winter discharges are correlated with the winter AO index in the Yenisei and Lena river basins, but winter discharge in the Ob River basin is associated with previous summer and fall moisture condition. The lagged relationships between precipitation and discharge are, in general, consistent with those found by Yang et al. (2002) in which the relationships are assessed at monthly time scales for the Lena River basin.

It is interesting to find that snow conditions have different seasonal impacts on discharges in different river basins. Maximum snow contributes to spring, summer, fall, and following winter discharges in the Ob, but to summer and fall discharges in the Yenisei, and to winter and spring discharges in the Lena River. The decreased time lag from western to eastern portions of the basins is probably, in part, related to the increased percentage of permafrost from the west to the east river basins (Zhang et al. 2001; Serreze et al. 2003). Permafrost acts as an impermeable barrier; winter precipitation or any melting snow are rapidly channeled into the streams of the Lena basin. Also, the higher proportion of highland areas in the river basin of the Lena, which supposedly results in a faster hydrological response, could be another important reason (Burn 1997). This also explains why longer lag effects of seasonal precipitation on summer river discharge are found in the Ob and Yenisei river basins rather than in the Lena River. For example, winter precipitation still affects summer discharge of the Ob and Yenisei Rivers, but spring precipitation instead of winter precipitation affects the Lena River's summer discharge.

Based on the revealed climatic variables contributing to the winter discharges of these rivers, the positive trends in winter discharges are likely related to the trends in climatic and atmospheric variables as pointed out by Peterson et al. (2002). In addition to human impact (Ye et al. 2003), the increasing winter discharge of the Ob and Yenisei river basins may be associated with the increased winter NAM index value and maximum snow depth. The winter and spring discharge trend of the Lena River may be associated with the positive trend of the winter and spring NAM index, maximum snow depth, and increasing winter and spring surface air temperatures as suggested by Yang et al. (2002).

In general, 35%–69% variance of spring discharges, 34%–47% variance of summer discharges, 21%–50% variance of fall discharges, and 18%–36% variance of winter discharges are explained by available surface climatic and atmospheric circulation variables. For annual total discharges, 31%–55% of total variances are explained by the surface climate and atmospheric circulation conditions. The least amount of variance explained is found in the winter season. Although less accurate measurements of winter discharge data are possible under ice (Grab et al. 2000; Pelletier 1990), it is understandable that atmospheric conditions alone have less effect on winter discharge in an extremely low temperature environment. In addition to the limited number of stations, some of the climatic factors that are the direct or indirect components of water balance are either very hard to measure or quantify while others are scarcely available. (i.e., evaportranspiration, sublimation of snow, solar radiation, soil moisture, permafrost, and active-layer depth). All of these probably contributed to the fact that only a limited percentage of the variation of the hydrological cycles of these high-latitude regions can be explained by the available atmospheric circulation and surface climate variables.

In addition to some unpredictable factors including human impact and the nature of chaos in the climate system, subsurface features including soil temperature and associated active-layer depth may also contribute to seasonal river discharge (Pavlov 1994, 1996). The active layer acts as a water reservoir that redistributes seasonal discharges by reducing warm-season and increasing cold-season discharges. It is suspected that increases in active-layer depth due to climate warming may provide some extra water supply for winter/spring discharge as hypothesized by other studies (e.g., Serreze et al. 2003; Yang et al. 2002). River ice thickness may also play a role in winter and spring discharges. Thinning river ice (Magnuson et al. 2000; Smith 2000) due to higher temperature and thicker snow accumulation is likely to increase the cold seasons' discharges, as was found in the Lena River by Yang et al. (2002).

In summary, this study further confirms that increasing trends in river discharges especially during cold seasons appear to be associated with the increasing atmospheric NAO/NAM index and with snow depth associated with increasing air temperatures and precipitation (Peterson et al. 2003). Atmospheric circulation and surface climatic variables explain up to a maximum of 69% of the seasonal and interannual variations of the three major river discharges over Siberia. The hydrological cycle over high latitudes is a complex process between surface and atmospheric interactions, and its variations cannot be completely explained by available atmospheric circulation and surface climate variables. Denser station distributions and development of methods to acquire new and sensible variables directly related to water balances are needed to better understand the hydrological process of the Arctic.

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