P1.7 THE IMPACT OF CLIMATIC CONDITIONS ON SEASONAL RIVER DISCHARGES IN SIBERIA

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1. INTRODUCTION

Three major rivers in Siberia, the Ob, the Lena, and the Yenisei, together contribute more than 45% of total freshwater inflow to the Arctic Ocean (Shiklomanov et al. 2000; Prowse et al. 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 goal of this study is to identify the critical climatic variables that are significantly associated with river discharges and assess the magnitude of variance that are explained by these surface and atmospheric circulation variables for each of the three Siberian river basins. This will clarify the significance of atmospheric and climatic conditions to the river discharges and thus improve our understanding of the hydrological and climatological processes of the Arctic.

2. DATA

Monthly river discharges during 1936-95 at three basin outlet stations, Salekhard on the Ob, Igarks on the Yenisei, and Kusur on the Lena rivers are used in this study. The data are from R-ArcticNET, originally collected and quality-controlled by the Russian Hydrometeorological Services. The discharge at each of these gauge stations is used to represent that river's basin-scale values.

Maximum snow depth and the first and last date of continuous snow cover data 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. Both maximum snow depth and the first and last date of continuous snow cover are interpreted into grid values of 5º latitude by 5º 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.

Surface air temperature and precipitation data are from the Jones et al., gridded 5º latitude by 5º longitude monthly global data set (Jones et al. 1994; Hulme 1991). Seasonal averages are derived from monthly values; basin-averaged seasonal air temperature and precipitation are derived from averaging the grid values within each basin.

David 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. Seasonal index values are averaged from the monthly values.

3. METHODS

To examine the linear associations between climatic or atmospheric circulation variable and seasonal river discharges, Pearson's correlation analysis is used. In the correlation analysis, seasonal lag correlations between climatic or atmospheric variable and river discharge is also included to examine the possible effects of seasonal and regional variations in ground water storage due to permafrost and the lags between snowmelt and rainfall-flood processes due to basin integration.

To reveal the discharge variance explained by climatic and atmospheric circulation variables, stepwise regression analysis is used to select significant variables contributing to seasonal and annual discharge variability. Due to high inter-correlations among these climatic variables and the AO index, factor analysis is applied to all 15 atmospheric and climatic variables to reduce them into a few major factors explaining the large variability of the original variables in each basin. The resulting factors are independent of each other and thus can be used in the stepwise analysis instead of inter-correlated original atmospheric or climatic variables. 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 atmospheric/climatic variables that affect the river discharges.

4. RESULTS

4.1 Correlation Results

For all three river basins, spring discharge is highly correlated with spring surface air temperature and negatively correlated to average snow cover ending date. This suggests the importance of spring air temperatures and related snow melting to the spring discharges. The statistically significant correlation between winter/spring AO index and spring discharge is perhaps through the AO's impacts on spring temperature for it is significantly correlated with spring air temperature ($p<0.001$).

One interesting result is the significant correlation of spring discharge to maximum snow depth in the Lena River basin. Also, spring discharge is positively correlated with spring precipitation in the Yenisei and Lena river basins. The direct contribution of spring precipitation and snow accumulation to spring discharge is probably due to the fact that the Yenisei and Lena river basins have higher percentages of permafrost ground. Permafrost acts as an impermeable barrier; spring precipitation and any melting snow are rapidly channeled into streams, especially in the Lena River basin. It is also likely associated with spring air temperature since spring air temperature is positively correlated with spring precipitation in the Yenisei and

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Lena river basins; correlation coefficients are 0.4486 and 0.3895 ($p<0.005$) respectively.

Snow cover ending date is positively correlated with summer discharge in all three river basins suggesting that the later the snow melting occurs the greater the summer discharge. Maximum snow depth and winter precipitation are positively correlated while spring air temperature is negatively correlated with summer discharge in the Ob and Yenisei river basins. This suggests that melting water from snow contributes to summer discharge in the Ob and Yenisei river basins. Higher spring air temperature accelerates spring melting and results in less snow for summer runoff. Greater maximum snow depth and winter precipitation will likely delay snow melt, resulting in higher 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 also 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 the summer discharge. This suggests that the influences of these variables are persistent through summer to fall season's discharge. The highest correlations occur with summer air temperature (-0.5419; $p<0.0005$) and summer precipitation (0.6592; $p<0.0005$). This suggests that summer precipitation contributes to fall discharge and that a cooler summer with lower evapotranspiration also results in a higher fall discharge. In the Yenisei river basin, fall discharge is positively correlated with maximum snow depth and summer precipitation. Summer precipitation has the highest correlation, with a coefficient of 0.4126. This suggests that both summer precipitation and snow contribute to fall discharge in the Yenisei River basin. In the Lena river basin, fall discharge is positively correlated with summer precipitation, and winter AO index. The highest correlation is with summer precipitation with a coefficient of 0.6487 ($p<0.0005$), suggesting that summer precipitation contributes most to the Lena River's fall discharge.

Winter discharge is negatively correlated with previous summer air temperature, positively correlated with previous snow maximum, summer precipitation, and fall precipitation in the Ob river basin. This implies that snow and summer and fall precipitation contribute to fall and early winter discharge and thus affect winter discharge. Similarly, higher summer air temperature increases evaportranspiration and reduces the amount of water available for winter runoff in the Ob River basin. The interesting thing is that winter climate conditions (temperature, circulation, and maximum snow) that influence winter discharge occur only in the Lena river basin. One possible explanation for the correlation to winter climatic variables is related to the higher area cover of permafrost in the Lena river basin. A warmer winter climate delays active layer freeze-up over permafrost, thus increasing winter discharge. Also, snow acts as an insulation layer; the thicker the snow the warmer the ground and later the freeze of the active layer contributes to higher discharge in winter. The authors speculate that the connection between winter AO and winter discharge is through winter air temperature that influences freezing dates of the active layer.

4.2. Factor Analysis Results

Factor analysis resulted in six factors for each of the three drainage basins. Each factor represents the combination of atmospheric/climatic conditions that are highly correlated with that factor. The names of each factors for each basin are listed in Table 1-3. In the Ob river basin, the 6 factors explain 69.67% variance of the original 15 atmospheric and climatic variables. In the Yenisei River basin, the six factors together explain 71.28% of the total original variance and 72.76% of variance is explained in Lena River basin.

4.3. Stepwise Regression Results

Stepwise regression results for spring discharge are listed in Table 1. As expected, Spring Heat is a significant contributor to spring discharge in all three rivers explaining 54.54%, 35.42%, and 39.20% variance of spring discharges for the Ob, Yenisei, and Lena Rivers respectively. Snow shows up as an important contributor to spring discharge for the Ob and Lena river basins also. Winter Climate and Spring & 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 68.72%, 35.42%, and 56.74% of the total variance of spring discharge for the Ob, Yenisei, and Lena river basins respectively.

Table 1. Regression Results of Spring River Discharge (Dependent Variable) and the Factors (Independent Variables)

	Variables	Stand. Reg.Coeff	R^2
Ob	Spring Heat Spring & Fall Moist. Winter Moist. & Snow	0.739 -0.324 0.191	0.5454 0.1050 0.0367
Yenisei	Spring Heat	0.595	0.3542
Lena	Spring Heat Snow Winter Climate	0.626 0.360 0.214	0.3920 0.1295 0.0459

Summer discharge results are shown in Table 2. Spring Heat and Winter Climate or Winter Moisture are important factors for summer discharge in all three rivers. Summer Climate or Summer Moisture contributes to the variability of summer discharge in the Ob and Lena rivers. Spring & Fall Moisture and Fall Moisture & 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 47.13%, 33.96%, and 34.34% in the Ob, Yenisei, and Lena river basins respectively.

Regression results for the fall season are shown in Table 3. Summer Moisture or Summer Climate is an important contributor for fall discharges in all three rivers, explaining 36.49%, 5.46%, and 36.07% of the fall discharge variance in the Ob, Yenisei, and Lena river basins respectively. Winter Moisture or Winter Climate is an important contributor for fall discharge in the Ob and Yenisei river basins. Also, Spring Heat in the Ob and Fall Heat in the Yenisei contribute to its fall discharge respectively. Total variances explained for fall discharge are 50.04%, 20.67%, and 36.07% for the Ob, Yenisei, and Lena river basins respectively.

Table 2. Regression Results of Summer River Discharge (Dependent Variable) and the Factors (Independent Variables)

	Variables	Stand. Reg. Coef.	R^2
Ob	Summer Climate	-0.400	0.1597
	Spring Heat	-0.364	0.1328
	Winter Moist. & Snow	0.318	0.1013
	Winter & Summer Circulation	-0.232	0.0536
	Spring & Fall Moist.	0.155	0.0239
Yenisei	Spring Heat	-0.499	0.2493
	Winter Climate	0.301	0.0904
Lena	Summer Moisture	0.426	0.1814
	Winter Climate	0.285	0.0811
	Fall Moisture & Summer Heat	-0.208	0.0433
	Spring Heat	-0.191	3.65

Table 3. Regression Results of Fall River Discharge (Dependent Variable) and Factors (Independent Variables)

	Variables	Stand. Reg. Coeff.	R^2
Ob	Summer Climate	-0.604	0.3649
	Winter Moist.	0.280	0.0784
	Spring Heat	-0.239	0.0571
Yenisei	Fall Heat	0.298	0.0888
	Winter Climate	0.252	0.0633
	Summer & Fall Moist.	0.234	0.0546
Lena	Summer Moist.	0.601	0.3607

Regression results for winter discharge are shown in Table 4. 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 basin, and Snow contributes to the Lena river basin winter discharge. Summer Circulation contributes to Yenisei and Winter Climate contributes to Lena river winter discharge. Total variances of winter discharge explained are 18.41%, 35.64%, and 20.06% 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 has a certain influence on the annual total discharge (Table 5). In the Ob river basin, a total of 48.23% of annual discharge is explained by Summer Climate, Winter Moisture, Winter & Summer Circulation, and Spring Heat. In the Yenisei River, Winter Climate, Fall Heat, Summer Heat & Spring Moisture, and Summer Circulation affect the annual discharge. In the Lena River, Summer Moisture, Winter Climate, Snow, and Fall Moisture & Summer Heat affect annual discharge. These factors explain a total of 48.23%, 30.92%, and 54.60% of the annual discharge totals in the Ob, Yenisei, and Lena rivers respectively.

Table 4. Regression Results of Winter River Discharge (Dependent Variable) and the Factors (Independent Variables)

	Variables	Stand. Reg. Coeff.	R^2
Ob	Spring & Fall Moist.	-0.341	0.1166
	Winter Moist.	0.260	0.0676
Yenisei	Summer & Fall Moist.	-0.407	0.1659
	Summer Circulation	0.301	0.0909
Lena	Snow	0.281	0.0787
	Fall Moist. & Summer Heat	0.248	0.0616
	Winter Climate	0.245	0.0602

Table 5. Regression Results of Annual total River Discharge (Dependent Variable) and the Factors (Independent Variables)

	Variables	Stand. Reg. Coeff.	R^2
Ob	Summer Climate	-0.501	0.2506
	Winter Moist.	0.411	0.1689
	Winter & Summer Circulation	-0.200	0.0398
	Spring Heat	-0.152	0.0231
Yenisei	Winter Climate	0.355	0.1262
	Fall Heat	0.287	0.0825
	Summer Heat & Spring Moist.	-0.233	0.0544
	Summer Circulation	0.215	0.0462
Lena	Summer Moist.	0.553	0.3055
	Winter Climate	0.361	0.1300
	Snow	0.262	0.0688
	Fall Moist. and Summer Heat	-0.204	0.0417

4. SUMMARY

The generally consistent 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 precipitation. (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 precipitation. These results are in general consistent with the lagged monthly association between air temperature and discharges revealed in the Lena River by Yang et al (2002).

It is interesting to find that snow conditions have different seasonal impacts on discharges in different river basins. Maximum snow accumulation 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 related to the increased permafrost fraction from the west to the east river basins (Zhang et al. 2001; Serreze et al. 2002). Permafrost acts as an impermeable barrier; winter precipitation or any melting snow are rapidly channeled into the streams of the Lena basin. This also explains why longer lag effects of seasonal precipitation on summer river discharge are found in the Ob and Yenisei rivers rather than in the Lena River. For example, winter precipitation still affects the summer discharge of the Ob and Yenisei rivers, but spring precipitation instead of winter precipitation affects the Lena River's summer discharge.

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 discharge are found to be explained by surface climatic and atmospheric circulation conditions. 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. Besides even though less accurate measurements of winter discharge data are possible under ice (Grabs et al. 2001; Pelletier 1990), it is understandable that atmospheric conditions alone have less affect on winter discharge in an extremely low temperature environment.

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