Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds

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[1] The consistency of long-term yearly precipitation and runoff trends over the largest Arctic watersheds (Ob, Yenisei and Lena Rivers) is examined. Three gridded precipitation datasets (Climatic Research Unit, University of Delaware, NCEP) are used for comparative analyses with runoff data collected at basin outlets. The results generally demonstrate inconsistency in long-term changes of basin precipitation and runoff. The Yenisei River runoff increases significantly, while precipitation data show mostly negative trends. The Ob River does not show any significant trend either in precipitation or runoff. Positive trend in the Lena River runoff is accompanied by a weak precipitation increase; however, the precipitation increase is not strong enough to support the observed runoff change. The inconsistency identified in basin precipitation and runoff trends suggests uncertainty in both the quality of basin precipitation and runoff datasets, as well as the perceived hydrologic factors impacting runoff change. *INDEX TERMS:* 9315 Information Related to Geographic Region: Arctic region; 1860 Hydrology: Runoff and streamflow; 1854 Hydrology: Precipitation (3354); 1833 Hydrology: Hydroclimatology; 1620 Global Change: Climate dynamics (3309). **Citation:** Berezovskaya, S., D. Yang, and D. L. Kane (2004), Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds, *Geophys. Res. Lett.*, *31*, L21502, doi:10.1029/2004GL021277.

1. Introduction

[2] The hydrologic cycle of Arctic Rivers is an important component of the global climate system. The Ob, Yenisei and Lena Rivers are the three largest rivers flowing into the Arctic Ocean, with mean discharge of 395, 610 and 532 km^3/yr respectively [*Korzoun et al.*, 1974]. Combined, they contribute as much as 1537 km^3/yr, approximately 46% of total river inflow into the Arctic Ocean. Arctic hydrological systems exhibit large temporal variability [*Kane*, 1997] due to large-scale changes in atmospheric circulation [*Walsh*, 2000]. Recent studies report significant changes in hydrological regime of the major Arctic rivers, such as an increase of yearly and winter streamflow [*Peterson et al.*, 2002], shift of peak discharge timing associated with earlier snowmelt [*Yang et al.*, 2003], and river-ice regime changes [*Smith*, 2000]. Among these changes, the mechanisms responsible for the yearly runoff increase are presently of special interest [*Peterson et al.*, 2002; *McClelland et al.*, 2004]. Recent analyses of permafrost thawing, dam regulation and fires show that none of these factors alone can generate the observed increase in river runoff [*McClelland et al.*, 2004]. *Peterson* [2002] correlated the river discharge increase with both the North Atlantic Oscillation through enhanced atmospheric transport of moisture from lower to higher latitudes and global air temperature rise.

[3] Among the basic components of the basin water budget, precipitation and runoff are the only variables measured directly on a regular basis. Station network in the Former Soviet Union provides the most complete long-term precipitation observation in the Arctic. Although the accuracy of precipitation records is considerably less than runoff measurements [*Fekete et al.*, 2004], spatial estimates from conventional gauge observations remain the primary source for studying precipitation variability over time. This study systematically analyzes long-term yearly precipitation (P) and runoff (R) data for the basins of the Ob (drainage area is 2990 * 10^3 km^2), Yenisei (2580 * 10^3 km^2) and Lena (2490 * 10^3 km^2) Rivers [*Korzoun et al.*, 1974] (Figure 1). The emphases of the work are to examine the consistency of yearly precipitation and runoff trends over the basins and to assess the role of precipitation variations in observed runoff changes. We also touch on some key processes of the interaction and feedback between climate and hydrology and data quantity and quality issues in the Arctic. The results of this study will be useful to ongoing national and international efforts for assessing recent changes in the hydro-climatology of the pan-arctic landmass and the terrestrial ecosystems [*Vörösmarty et al.*, 2001]. They will also improve our understanding of hydrologic response to climate change and variation in the high latitude regions.

2. Datasets and Analysis Methods

[4] The annual runoff depth distributed over the basin from 1936 to 1998 for the outlet stations were obtained from the ArcticNet 3.0 [*Lammers et al.*, 2001]. Comparison of available major global precipitation datasets showed that there are only a few that can represent our current understanding of precipitation distribution [*Legates*, 1995; *Fekete et al.*, 2004]. This analysis uses the long-term monthly precipitation datasets of the Climatic Research Unit (CRU) [*New et al.*, 2000], University of Delaware (UDel) (C. J. Willmott and K. Matsuura, Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999) version 1.02, 2001, available at http://climate.geog.udel.edu/~climate), and the National Centers for Environmental Prediction (NCEP) [*Kistler et al.*, 2001]. These datasets have different spatial and temporal resolutions and record length. The spatial resolutions are 2.5° × 3.75° for the CRU, 1.9° by 1.9° for the NCEP, and 0.5° × 0.5° for the UDel. The spatial coverage of the CRU dataset

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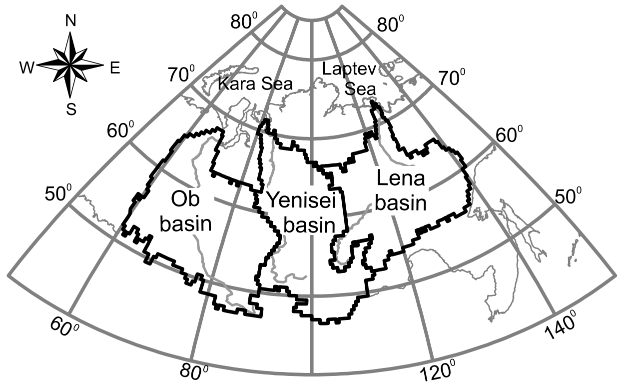

Figure 1. The three largest Arctic watersheds (the Ob, Yenisei and Lena River, Siberian region).

is not uniform; approximately 40% of grid cells are consistently missing for the entire period of time. The basin means have been estimated by averaging all available grid cells within a basin. The CRU precipitation covers the period of 1900–1998, the NCEP fields are available from 1948 to 2003. The UDel precipitation dataset version 1.02 has been taken from the ArcticRIMS website for the period from 1950 to 1999.

[5] To examine the consistency between the three datasets, basic statistical characteristics of the precipitation records (annual mean, standard deviation and spatial and temporal correlation) were compared for the common period from 1950 to 1998. The UDel dataset shows the lowest long-term mean annual precipitation (353–420 mm) over the three basins, whereas the NCEP provides the highest values (622–728 mm) (Table 1). The interannual variations, measured by standard deviations, are similar between the UDel and CRU datasets, but much higher for the NCEP. Relative to UDel and CRU, the NCEP annual means and standard deviations are generally higher by a factor of 1.5. *Serreze and Hurst* [2000] reported that severe overestimation of summer precipitation is the most significant problem with the NCEP model. Since summer precipitation dominates the annual totals, the estimates of annual sums are exaggerated by the NCEP. In terms of temporal compatibility, basin mean precipitation shows higher correlations between the CRU and UDel datasets, varying from 0.85 to 0.96 among basins, and relatively low correlations of 0.40–0.65 with the NCEP. The NCEP precipitation is substantially different than the other two precipitation datasets.

[6] Trends in yearly precipitation (P) and runoff (R) were evaluated by the least-squared linear regression analyses and represented by slope of regression line (a). Significance of the trend was tested using $|a/\sigma_a| > t_{1-\alpha}$, where σ_a is the standard error of estimate and $t_{1-\alpha}$ is a quantile of the Student's t-distribution at two-tailed significance level $2\alpha = 10\%$. The potential increase of precipitation required to generate runoff change was calculated using runoff ratio (R/P) and runoff trend. Estimated precipitation trend is the runoff trend divided by runoff ratio, assuming no major changes in evapotranspiration and basin storage. By comparing observed and estimated precipitation trends, the compatibility of P and R changes was examined.

Table 1. Annual Mean (AM) and Standard Deviation (SD) of Precipitation Data for the Period 1950–1998 (mm)

	Ob Basin		Yenisei Basin		Lena Basin	
Data Set	AM	SD	AM	SD	AM	SD
UDel	420	34.2	400	21.7	353	28.3
CRU	445	35.4	433	21.7	392	34.5
NCEP	695	57.0	728	43.6	622	55.2

3. Precipitation and Runoff Trends

[7] Trend analysis is restricted to two periods: 1950–1998 and 1936–1998. Since all precipitation and runoff datasets are available between 1950 and 1998, this period was chosen as the common time frame for the comparative analysis. The second period is the time over which a significant runoff increase has been observed [*Peterson et al.*, 2002]. Only the CRU dataset is long enough to study the precipitation variability from 1936 to 1998.

3.1. Period From 1950 to 1998

[8] Studies show that runoff ratios vary over Siberia due to differences in climatic and hydrologic conditions [*Korzoun et al.*, 1974; *Serreze et al.*, 2002]. Precipitation has less impact on the Ob River discharge in comparison to the other two basins because a higher fraction of annual precipitation is lost through evapotranspiration [*Serreze et al.*, 2002]. *Korzoun* [1974] reported that the Ob basin yearly evaporation accounted for 74% of annual precipitation. Although it has the highest mean precipitation, the Ob River has relatively low runoff of 131 mm and lowest runoff ratio of 0.24 to 0.26. The low runoff ratio is caused by regional climatic conditions, high percent of ponds/wetlands, land use/vegetation conditions and the lower spatial extent of permafrost in western Siberia. The areal distribution of permafrost is higher in central and eastern Siberia; runoff ratios consequently increase to the east with 0.42–0.48 for the Yenisei River basin and 0.46–0.55 for the Lena River.

[9] The Ob River has a weak positive yearly runoff trend of 4 mm/49yr. *Yang et al.* [2004] correlated this runoff change with summer precipitation increase by about 5–10% per decade over northwest Siberia. The CRU and UDel datasets show weak positive precipitation change (1 to 13 mm/49yr), whereas the NCEP suggests a negative precipitation trend of about 29 mm/49yr. Although the trends in precipitation and runoff are not statistically significant (Table 2), there seems to be a consistency in their long-term changes over the Ob basin. Given the long-

Table 2. Total Trend in Precipitation (P) and Runoff (R) for the Overlap Period 1950–1998 and Estimated Precipitation Change Necessary to Support Observed Runoff Trend (mm/49yr)

	Total P Trend							
Basin	CRU	UDel	NCEP	R Trend	k_1	R/k_1	k_2	R/k_2
Ob	+1.0	+12.7	−28.9	+4.4	0.24	+18.3	0.26	+16.9
Yenisei	−15.7[a]	−9.8	−64.7[a]	+20.[a]	0.42	+49.0	0.48	+42.9
Lena	−10.8	−9.8	−83.8[a]	+14.7	0.46	+32.0	0.55	+32.0

[a]Indicates significant trend at least at 90% confidence interval. k_1 and k_2 are runoff ratios (dimensionless) from *Korzoun et al.* [1974] and *Serreze et al.* [2003] respectively.

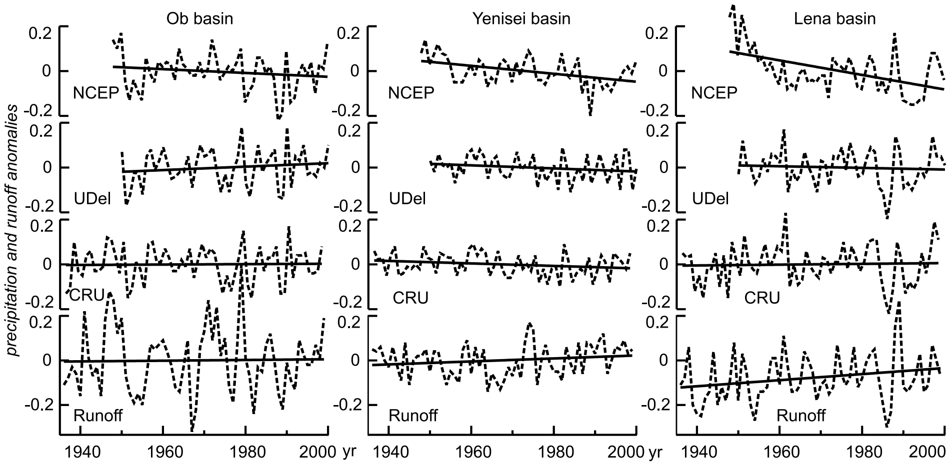

Figure 2. Basin annual precipitation (upper three graphs) and runoff (lower graph) anomalies (normalized deviations from the mean). Dashed lines show annual anomalies and the solid lines indicate trends.

term runoff trend, runoff ratios were used to quantitatively estimate the magnitude of precipitation change necessary to generate the runoff trends. The results show that, for the runoff rise of 4 mm/49 yr, yearly precipitation should increase by 17–18 mm/49yr (Table 2). These estimated changes are slightly higher than the observed precipitation trends (maximum of +13 mm/49yr from the UDel data).

[10] The Yenisei River annual runoff shows an increase of about 21 mm/49yr. This change is statistically significant at 90% confidence interval. Basin precipitation trends are however negative, ranging from −10 mm/49yr (UDel) to −65 mm/49yr (NCEP). This result clearly indicates inconsistency in runoff and precipitation changes over the Yenisei watershed. Furthermore, using the runoff ratios from *Serreze et al.* [2002] and *Korzoun et al.* [1974], the required precipitation increases should be 43–49 mm/49yr to support the observed runoff increases (Table 2).

[11] The total Lena River runoff change is an increase of 15 mm/49yr, which is statistically significant at 75% confidence interval (Table 2). The NCEP dataset shows a statistically significant negative trend of −84 mm/49yr. The other two datasets also show negative changes of about −10 mm/49yr. Applying runoff ratios to runoff trend, we should expect a precipitation increase of 32 mm/49yr to support 15 mm runoff rise over the period 1950–1998 (Table 2).

[12] Yearly precipitation and runoff records are presented in Figure 2 for the three basins. They demonstrate considerable inconsistency in precipitation and river runoff changes over the period 1950–1998, particularly for the Yenisei and Lena basins. Positive trends in river runoff are accompanied by negative trends in basin precipitation. In addition, the NCEP dataset for all cases suggests implausible precipitation decreases over this period (Figure 2).

3.2. Period From 1936 to 1998

[13] The Yenisei and Lena River's runoff data demonstrate positive trends of 9 and 20 mm/63yr respectively. The trend for the Lena River is statistically significant at 90% confidence interval (Table 3). Given an estimated runoff increase, we would expect corresponding precipitation increases of 18–21 and 37–44 mm/63yr over this period in the Yenisei and Lena basins respectively. Similar results were reported by *Holmes et al.* [2003]. They estimated that the mean precipitation would have to increase by 30 mm/64yr for the six largest Siberian watersheds during 1936 to 1999 in order to generate the observed runoff increase of 14 mm/64yr. By contrast, the CRU precipitation during 1936–1998 shows a negative trend of −16 mm/63yr for the Yenisei watershed and a weak upward trend of 4 mm/63yr for the Lena basin (Table 3). The Ob River has no significant trends in both precipitation and runoff during the observation period (Table 3).

4. Discussion and Summary

[14] The consistency of yearly precipitation and runoff trends in the Ob, Yenisei and Lena Rivers were analyzed with the intent to assess the role of precipitation variations on discharge changes. Analysis was focused on three commonly-used precipitation datasets that represent our current understanding of spatial and temporal distribution of precipitation. The results exhibited different associations between basin runoff and precipitation over the three large Siberian rivers. Precipitation changes have relatively weak influences on the Ob River runoff due to a low runoff ratio. The impact of weak precipitation increases to runoff change in the Ob basin was difficult to detect, particularly given small changes in yearly runoff. Changes in the Yenisei River runoff can not be explained by trends retrieved from the CRU, UDel and NCEP precipitation datasets; positive trends in river runoff are accompanied by negative precipitation trends. Similarly, a positive runoff trend was accompanied by negative precipitation trends during 1950–

Table 3. Total Trend in Runoff (R) and CRU Precipitation (P) Over the Period 1936–1998 and Estimated Precipitation Change Necessary to Support Observed Runoff Trend (mm/63yr)

Basin	R Trend	P Trend	R/k_1[a]	R/k_2[a]
Ob	−0.63	+1.9	−2.6	−2.4
Yenisei	+8.8	−15.8[a]	21.0	18.4
Lena	+20.2[a]	+3.8	43.8	36.6

[a]Indicates significant trend at least at 90% confidence interval. k_1 and k_2 are runoff ratios (dimensionless) from *Korzoun et al.* [1974] and *Serreze et al.* [2003] respectively.

1998 over the Lena River. There was a weak positive precipitation trend from 1936 to 1998; however, it was not strong enough to support the observed Lena River runoff increase.

[15] When interpreting these results, patterns in increasing trends of runoff from Siberian Rivers can not be resolved from the apparent lack of consistent positive trends in the considered precipitation datasets. The inconsistency in yearly precipitation and runoff trends over the large watersheds also suggests both incompatibility and uncertainty in the quality of basin precipitation and runoff datasets. Temporal and spatial sampling techniques affect the quantification of large-scale precipitation data and climatology [*Hulme and New*, 1997]. Measurement biases are also very important, particularly for the cold regions where snowfall is a significant fraction of annual precipitation [*Yang et al.*, 1998]. We have efforts underway to enhance the quality of arctic regional precipitation data.

[16] Another issue of this research is that although the three large rivers examined here had positive trends in runoff, not all of them experienced similar runoff increases. The Ob, Yenisei and Lena watersheds are the largest in the Arctic, and each of them is characterized by unique climatic conditions and distinctive factors affecting runoff (relief, permafrost distribution, lake storage, anthropogenic impacts, etc.). This straightforward analysis shows that the magnitude of runoff change varies significantly between these three watersheds (the Ob basin demonstrated only minimal changes). This implies that there is no "universal" factor driving runoff increase, but runoff changes are basin specific and can be regulated by different factors in each basin. In this respect, along with precipitation, the role of evapotranspiration and anthropogenic impacts should not be ignored. It is known that anthropogenic impacts are significant over the Ob and Yenisei basins, mainly due to land use changes and construction of large dams [*Yang et al.*, 2004]. Changes in cloud and radiation forcing due to large-scale circulation changes [*Wang and Key*, 2003] may affect regional annual evapotranspiration, which is comparable in magnitude with annual runoff for Siberian Rivers [*Korzoun et al.*, 1974]. Currently, we are investigating the role of evapotranspiration variability and human impacts relative to streamflow changes.

[17] Conventional wisdom would suggest that increased precipitation would be needed to produce additional runoff. An exception to this logic would be the loss of water from storage (lakes, glaciers, subsurface, etc.), however this would be a transient process with the source eventually becoming depleted. Results from this paper direct our attention to the quality of the precipitation and runoff data and the question, is the quality sufficient to make accurate trend predictions or to support the conclusions reached in numerous papers on Arctic hydrologic change? We have only exposed the question in this paper, not answered it.

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