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# Divergence in seasonal hydrology across northern Eurasia: Emerging trends and water cycle linkages

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[1] Discharge from large Eurasia rivers increased during the 20th century, yet much remains unknown regarding details of this increasing freshwater flux. Here, for the three largest Eurasian basins (the Ob, Yenisei, and Lena) we examine the nature of annual and seasonal discharge trends by investigating the flow changes along with those for precipitation, snow depth, and snow water equivalent. On the basis of a multiperiod trend analysis and examination of station data, we propose two characteristic regimes to explain the long-term discharge increase from these large Eurasian rivers. Over the early decades from approximately 1936 to 1965, annual precipitation correlates well with annual discharge, and positive discharge trends are concurrent with summer/fall discharge increases. The latter decades were marked by a divergence between winter/spring flows, which increased, amid summer/fall discharge declines. A comparison of cold season precipitation (CSP) and spring discharge trends across subbasins of the Ob, Yenisei, and Lena shows limited agreement with one precipitation data set but good agreement ($R^2 > 0.90$) when a second is used. While natural variability in the Arctic system tends to mask these emerging trends, spatial and temporal changes can generally be characterized by increased solid precipitation, primarily to the north, along with a drier hydrography during the warm season.

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## 1. Introduction

[2] The Earth's higher latitudes are experiencing significant change, manifested by alterations that are widespread and have the potential to affect the larger earth system. Permafrost is warming across Alaska, Siberia, and other high-latitude regions [*Osterkamp*, 2005; *Walsh*, 2005; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007], with potential implications including changes in biogeochemical fluxes to the Arctic Ocean [*Frey and McClelland*, 2009] and increases in river discharge [*Lawrence and Slater*, 2005]. Freeze/thaw cycles are shifting [*McDonald et al.*, 2004], which may be a contributing factor in observed land cover change [*Chapin et al.*, 2005]. Evidence has gathered that significant changes are occurring to the arctic hydrological cycle [*White et al.*, 2007]. A study of historical satellite data suggests that a widespread decline in lake abundance across Siberia has occurred [*Smith et al.*, 2005]. Combined river discharge from the six largest Eurasian rivers increased over the period 1936–1999 [*Peterson et al.*, 2002], and analysis of provisional year 2007 data for these rivers suggests that a new historical maximum for combined annual discharge may have occurred [*Shiklomanov and Lammers*, 2009; Arctic Report Card, 2008, available at http://www.arctic.noaa.gov/reportcard/index.html]. In discussing their findings, *Frey and Smith* [2003] speculated that the increases in winter precipitation should affect the volume of freshwater input to the Arctic Ocean. While the potential exists for future alterations in the ocean thermohaline circulation to occur if the discharge increases were to continue [*Broecker*, 1997], a recent modeling study furthered the notion that the location of freshening is important in any response of the Atlantic meridional overturning circulation [*Rennermalm et al.*, 2006]. Most of these changes are well captured in global climate models (GCMs), although some uncertainty exists for projections of the magnitude of future alterations.

[3] Warming projected under several global change scenarios has the potential to significantly alter the water cycle within and in close proximity to river basins across which arctic rivers derive their flow. Warming is expected to lead to increases in net precipitation at high latitudes [*IPCC*, 2007]. Much of the increase is expected to occur during winter [*Kattsov et al.*, 2007]. By midcentury, annual river runoff is projected to increase by 10–40% at high latitudes and decrease by 10–30% over some dry regions of the

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midlatitudes [*IPCC*, 2007]. *Holland et al.* [2007] found that models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) showed an acceleration of the Arctic hydrological cycle, with increases in precipitation outpacing increases in evaporation and transpiration. A qualitative agreement between the models, for which the only common forcing is rising greenhouse gas concentrations, implicates this greenhouse gas loading as the cause of the change. Increases in river discharge from Eurasia into the Arctic Ocean were noted in simulations with the HadCM3 general circulation model [*Wu et al.*, 2005]. Model projections for northern Europe, however, have been found to generally underestimate the recent change in winter precipitation [*Bhend and von Storch*, 2008]. Over most midlatitude continental interiors, models predict a drying trend in summer [*IPCC*, 2001]. In an examination of station data, *Ye and Fetzer* [2009] found that, for stations across southern Eurasia, vapor pressure decreases with increasing air temperature during summer. This suggests that the region is moisture limited during the warmer months.

[4] As reported by *Peterson et al.* [2002], combined river discharge from the six largest Eurasian rivers (hereinafter referred to as the Eurasian6) increased by 2.0 $km^3$ $a^{-2}$ over the period 1936–1999. This is equivalent to an increase of approximately 0.21 mm $a^{-2}$ averaged over the 9.31 million $km^2$ region. While dams are not believed to be the primary cause for this trend in annual discharge [*McClelland et al.*, 2004], flow regulations can have a significant effect on seasonal fluxes. Significant increases (25% to 90%) in discharge from the Lena basin observed at Kusur for the months of October–April (1935–1999) were described by *Yang et al.* [2002], who also suggested that the level of statistical significance of trends for summer (July–September) months were lower compared to those for winter and spring seasons. These winter trends are largely due to water release from a large dam on the Vilyuy River. River discharge across this region is affected by several major hydroelectric dams which were constructed beginning in the mid-1950s. The Yenisei River is the most heavily regulated among the Ob, Yenisei, and Lena [*Adam et al.*, 2007]. Dam regulation significantly obscures climate related runoff variability [*Ye et al.*, 2003]. The impoundments tend to dampen natural runoff trends in summer and enhance the trends in winter and fall seasons [*Yang et al.*, 2004a]. For example, dams account for most (70 to 100%) of the long-term trends in winter discharge observed at the downstream sites of the Ob, Yenisei, and Lena basins [*Adam et al.*, 2007]. It has been estimated that the two large reservoirs in the Yenisei basin (Bratskoje and Krasnoyarskoje, total volume more than 240 $km^3$) have increased winter low flows by 25% to 45% and decreased summer flows by 10% to 50% over the period 1935–1999 [*Yang et al.*, 2004a]. Impoundments have a lesser effect on trends in spring discharge, with the greatest influences during early spring (e.g., March and April) [*Adam et al.*, 2007]. Dam effects on long-term annual discharge trends are relatively insignificant, as are impacts due to consumptive use of water [*Shiklomanov*, 1997]. However, anomalously low flows can be observed for several years during times of reservoir filling [*Ye et al.*, 2003].

[5] While it is clear that dams have a large effect on seasonal (primarily winter) flows and confuse our interpretation of any real trends, natural causes cannot be discounted entirely. Indeed, positive trends in minimum daily discharge (or "low flows") have been reported across watersheds devoid of dam regulation [*Smith et al.*, 2007]. However, in an examination of discharge records from 139 sites over the Eurasian Arctic, *Shiklomanov et al.* [2007] found no evidence of widespread trends in extreme (high) discharge. Among these river basins, increases in precipitation generally explain discharge trends for the Severnaya Dvina in North European Russia, particularly the positive ones [*Adam and Lettenmaier*, 2008], and although no long-term trends for the Kolyma basin (extreme northeastern Siberia) have occurred, annual discharge declined by 1.5% over the period 1978–2000 [*Majhi and Yang*, 2008]. Characterizing the spatial and temporal variability in seasonal precipitation and discharge across the three large basins of central Eurasia (the Ob, Yenisei, and Lena) is thus central to our understanding of potential mechanisms contributing to the long-term discharge increase for the combined flow of the Eurasian6 [*Peterson et al.*, 2002].

[6] Recent studies have helped to narrow the focus on likely mechanisms behind the annual trend. The influence of fires, dams, and melting of permafrost are generally believed to be largely incapable of producing the increased annual flux from the Eurasian6 [*McClelland et al.*, 2004]. Studies for this region have tended to use annual precipitation [*Berezovskaya et al.*, 2004; *Pavelsky and Smith*, 2006; *Adam and Lettenmaier*, 2008] which masks important seasonal trend differences. Although precipitation across the three large basins, the Ob, Yenisei, and Lena, individually, exhibit no trend over the period 1936–1999 [*Berezovskaya et al.*, 2004], there is general agreement in the sign of changes in annual precipitation and river discharge among a collection of the region's smaller basins [*Pavelsky and Smith*, 2006]. Approximately 75% of the reported discharge increase arises from the Lena and Yenisei rivers, with no significant change for the Ob River [*Berezovskaya et al.*, 2004]. While it has been suggested that increases in minimum daily flows across these same small basins may be due to a reduction in the intensity of seasonal ground freezing [*Smith et al.*, 2007], it is unclear how extensive and influential these linkages are during winter. In a study which incorporated the effects of dams, *Adam and Lettenmaier* [2008] noted a divergence in discharge and precipitation trends, which has accelerated since the early 1960s.

[7] Changes in solid precipitation measures, in agreement with model studies, have been documented across the northern high latitudes of Eurasia. *Ye et al.* [1998] found that snow depth increased over most of northern Russia and decreased over most of southern Russia between 1936 and 1983. *Frey and Smith* [2003] found significant positive trends in winter precipitation (4–13%/decade) at 4 of 10 stations examined. *Ye and Ellison* [2003] determined that snowfall season length has increased during 1937–1994 due to earlier and later snowfall dates over north central and northwest Asia. *Rawlins et al.* [2006] examined trends in rainfall and snowfall derived from precipitation data in the data sets from Willmott-Matsuura (hereafter referred to as WM) (C. J. Willmott and K. Matsuura, Arctic terrestrial air

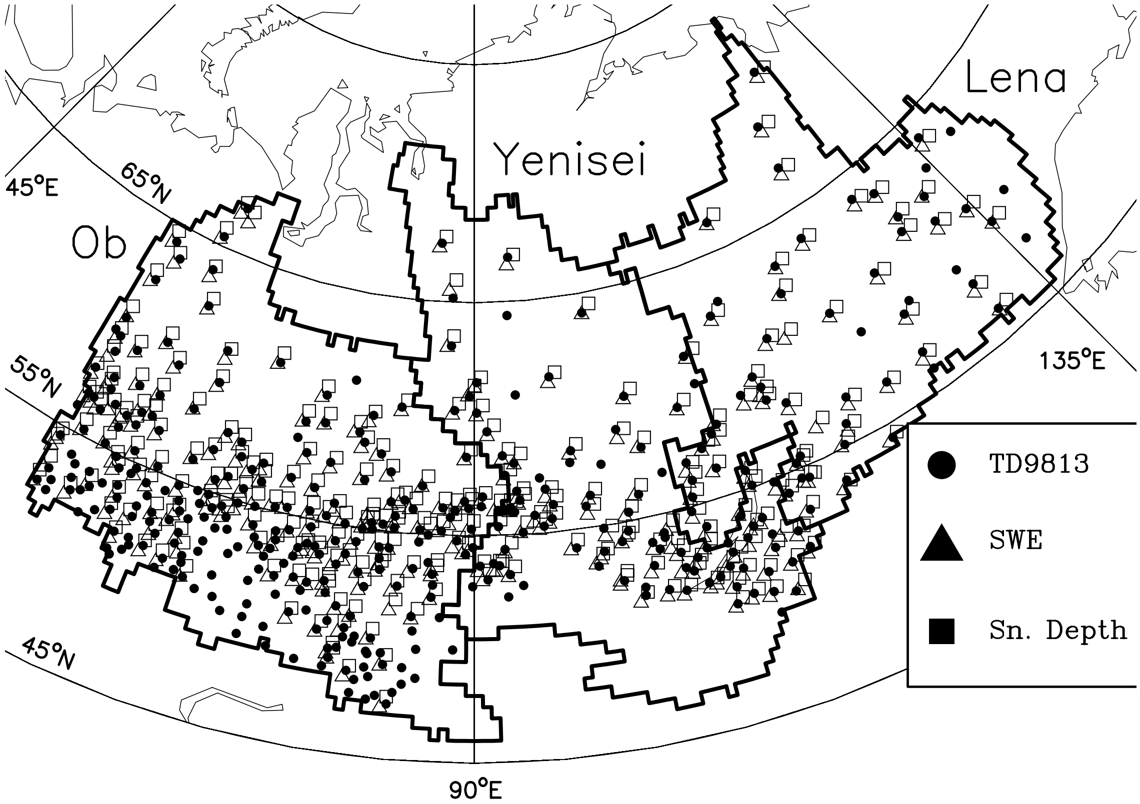

**Figure 1.** Locations of stations in the TD9813 data set (National Climatic Data Center, 2005) and the Former Soviet Union Hydrological Snow Surveys [*Krenke*, 1998] which fall within the (west to east) Ob, Yenisei, and Lena river basins. Filled circles, triangles, and squares mark the TD9813 precipitation, snow depth, and snow water equivalent (SWE) station locations, respectively. Symbols of colocated stations are slightly offset.

temperature and precipitation: Monthly and annual time series (1930–2000) version 1, 2001, available online at: http://climate.geog.udel.edu/~climate/), Climate Research Unit (CRU) [*Mitchell et al.*, 2004, available at http://www.cru.uea.ac.uk/], and NCDC's Dataset 9813 (hereafter TD9813) (National Climatic Data Center, Daily and subdaily precipitation for the former USSR, 2005, available at http://www.ncdc.noaa.gov/oa/documentlibrary/surface-doc.html9813), over the period 1936–1999, and found similar patterns as those depicted in the station data, namely, local increases in snowfall across the northern part of the Ob, Yenisei, and Lena basins, and a sustained and significant decrease in derived rainfall across the Eurasian6. An increase in the duration of the period with snow on the ground over Russia and the Russian polar region north of the Arctic Circle has also been found. Examining the synoptic network encompassing some 2100 stations within the boundaries of the former Soviet Union, *Groisman et al.* [2006] described increases of 5 days (Russia) and 12 days (Russian polar region) due to a fall (October–November) redistribution between snow cover and frozen soil and/or area with remnants of snow cover, but suggested that the changes cannot be directly linked with warming observed over the same time period.

[8] Given what has been learned about the increasing river discharge, potential agents of change, and the alterations in solid precipitation measures across the region, examination of the spatial and temporal characteristics in precipitation and river discharge can help establish linkages between these key water cycle components. The focus of our study, then, is on the nature of seasonal discharge trends for the combined flow of the three large Eurasian river basins over the period from 1936 to 1999 and on the relationship between precipitation and discharge across subbasins of the region for 1966–1995. In referring to the three-basin region, for example, when a spatial average is described, we use the acronym "OYL." Section 2 describes the data and methods employed in our analysis. Section 3 focuses on annual and seasonal trends in river discharge from the OYL region. Section 4 describes trends in precipitation, snow depth, and snow water equivalent (SWE). Section 5 links precipitation and discharge trends across subbasins of the OYL basins. Discussion and conclusions are provided in section 6. Through our use of independent data sets representing precipitation flux to the landscape and river discharge to the ocean, we describe the most important spatial and temporal variations and recent changes between these elements of the arctic water cycle across northern Eurasia.

## 2. Data and Methods

[9] Our analysis is based largely on precipitation observations made at meteorological stations (Figure 1) and

discharge records from the OYL rivers. Regarding precipitation uncertainties, wind-induced ‘‘undercatch’’ is typically the largest source of error in gauge-based precipitation records for Arctic regions, and is often very large in winter because of the increased effect of wind on solid precipitation. Efforts such as the World Meteorological Organization (WMO) Solid Precipitation Measurement Intercomparison Project have sought to reduce biases by quantifying the undercatch of several types of precipitation gauges [*Goodison et al.*, 1998]. Shielded gauges such the Tretyakov, in use across Russia, tend to perform better in windy environments. One of the major advantages of the WMO project resides in the fact that intercomparisons for different gauges were performed at several sites. Bias estimates from the effort have been applied at high latitudes and have resulted in significantly higher estimates of precipitation [*Yang et al.*, 1998; *Yang*, 1999]. In quantifying the effects of undercatch for over 4800 arctic station, *Yang et al.* [2005] estimated large negative biases of 80–120% in winter, with relatively small biases (<10%) noted for summer. Biases in precipitation trends can occur when drawn from gridded fields produced from station data derived from networks which change over time [*Rawlins et al.*, 2006; *Willmott et al.*, 1994].

[10] Monthly station precipitation time series in the present study are taken from TD9813 (National Climatic Data Center, 2005), which originated at the Russian Institute for Hydrometeorological Information, Obninsk, Russia. These data have been adjusted for biases due to the aforementioned wind effects, for station moves, and for changes in observing practices. A total of 2188 stations are contained within the TD9813 archive, with 1381 stations having at least 83% of valid daily data during the period 1961–1990. Typical of data archives for the Arctic, the density of stations falls off rapidly moving north (Figure 1). In the analysis to follow we define cold season precipitation (CSP) to be the total precipitation over the months of October–April, with summer precipitation as the total precipitation for the warm June–August period. This choice of period avoids the transitional months of May and September when some river basins may experience rain, and some may experience snow. An important distinction between TD9813 and other common data products is the inclusion of individual gauge observations. We make use of these individual point observations in examining the geography of changes in precipitation across the region.

[11] For our characterization of seasonal precipitation we also draw upon records from the Former Soviet Union Hydrological Snow Surveys [*Krenke*, 1998], which contain observations from 1345 sites throughout the Former Soviet Union between 1966 and 1990 and at 238 of those sites between 1991 and 1996 (Figure 1). These include snow depths at World Meteorological Organization (WMO) stations and snow depth and snow water equivalent from nearby transects. Snow depths in the data set are a 10-day average of individual snow depth measurements. The transect snow depth data are the spatial average of 100 to 200 individual measuring points. The transect snow water equivalent is the spatial average of twenty individual measuring points.

[12] Monthly river discharge records for the Ob, Yenisei, and Lena, extending back to 1936 as recorded at the most downstream station of each basin, are taken from R-ArcticNet V4.0 (http://www.r-arcticnet.sr.unh.edu/) [*Lammers et al.*, 2001; *Shiklomanov et al.*, 2002]. Analysis is also performed over 28 ‘‘subbasins’’ which are nested within the three large basins (Figure 2 and Table 1). These subbasins were selected under the requirement that all have a drainage area greater than 20,000 km$^2$ and no more than 2 years with a missing April, May, or June observation over the period 1966–1995. The focus on spring discharge in the subbasin analysis necessitated our screening for missing April–June observations. Uncertainties in annual and seasonal discharge estimates are likely in the range of ±10% [*Shiklomanov et al.*, 2006]. The 1966–1995 period, the primary focus of our analysis, was chosen based on the available snow survey records (beginning in 1966) and TD9813 data which end in the mid-1990s. This period was one of significant warming, as surface air temperatures increased from early century to the mid-1940s, decreased until about the mid-1960s, and then rose sharply through the end of the century [*Arctic Council*, 2005].

[13] Adjustments are made to raw discharge records for several subbasins within the Yenisei and Lena regions to remove dam influences on annual and seasonal discharge totals. For Yenisei subbasins we use the Hydrograph Routing Model (HRM) to reconstruct naturalized river discharge for the outlet of the Yenisei at Igarka and for four upstream subbasins. These subbasins are defined by the river discharge gauges at Bazaikha, Boguchany, Podkamennaya Tungus, and Yeniseysk. The model routes observed daily hydrographs from upstream to downstream gauges using the Duhamel integral approach [*Shiklomanov*, 1994]. The HRM does not include water budget computations, and thus provides more accurate hydrograph simulations than the water balance modeling approach used by *Adam et al.* [2007]. In that study, to minimize the errors due to runoff simulation in the VIC model, Adam et al. bias corrected the streamflow entering the most upstream reservoir on each of the regulated tributaries of the Ob, Yenisei and Lena rivers. Streamflow observations used for bias correction were taken from the nearest gauge for the reservoir. If the streamflow gauge was downstream of the reservoir, only the predam streamflow was used for bias correction. The reconstructions in the present study are made for monthly discharge since 1956 for each of these subbasins with the exception of the Yenisei at Bazaiha, for which reconstructed flows are begun in 1967. For Lena subbasins our adjustments involve linear regressions of monthly discharge between the regulated gauging station and an unregulated upstream station over the unregulated period. The regression equation is then used to reconstruct discharge for the regulated site. This was done for the Lena at Kusur (the most downstream site) and for the Vilyuy River at two locations, Khatyrik-Khomo and Suntar. No adjustments are made for subbasins of the Ob River. Only one large dam is located within the basin, and while its capacity ($\sim$50 km$^3$) exceeds the typical winter (DJF) flow ($\sim$37 km$^3$ total over the 3 months) observed at the basin outlet at Salekhard, the storage volume is only 13% of the mean annual flow. In addition, discharge for the lower Ob is heavily influenced by an abundance of lakes and wetlands throughout the middle portion of the basin which redistribute water between seasons. Water withdraws and diversions for agricultural and industrial purposes

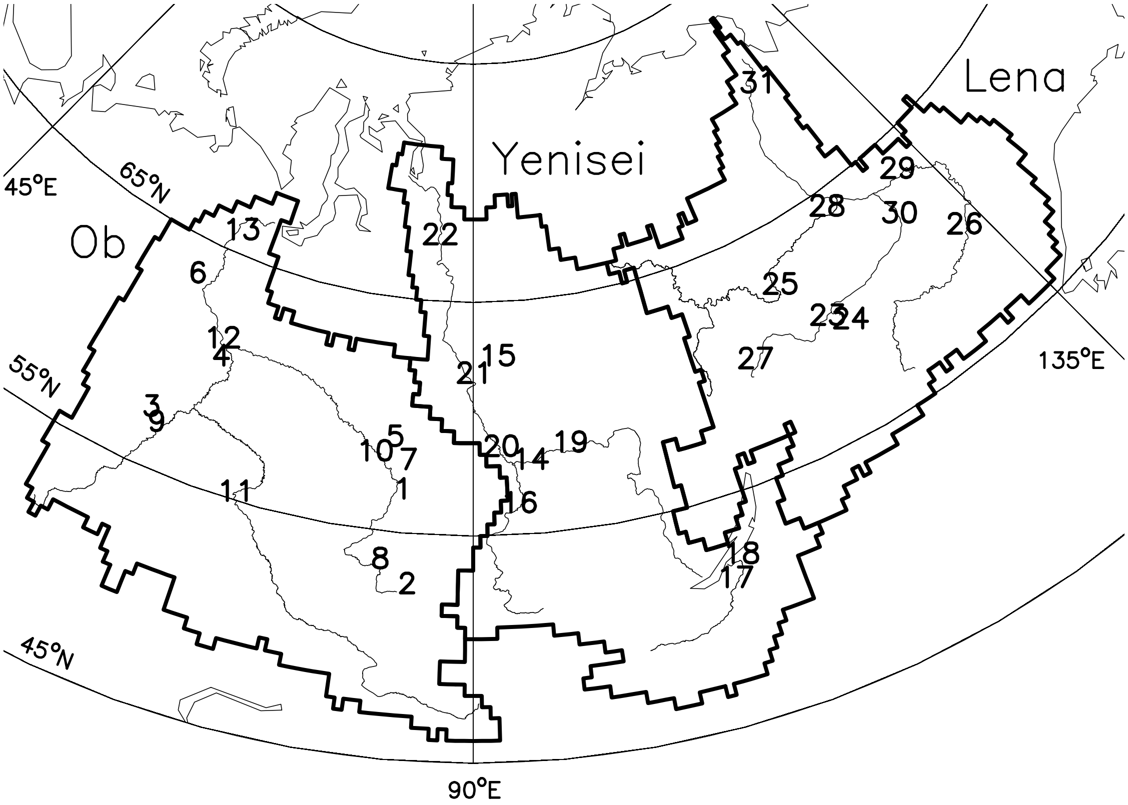

**Figure 2.** Locations of river gauges for the 31 subbasins listed in Table 1.

**Table 1.** Subbasins of the Ob, Yenisei, and Lena Drainage Basins Examined in This Study

| Index | Station Name | Basin | Latitude (°N) | Longitude (°E) | Area (km$^2$) |
|---|---|---|---|---|---|
| 1 | Tom' at Tomsk | Ob | 56.50 | 84.92 | 57000 |
| 2 | Katun' at Srostky | Ob | 52.42 | 85.72 | 58400 |
| 3 | Tura at Tumen' | Ob | 57.17 | 65.53 | 58500 |
| 4 | Konda at Altay | Ob | 60.33 | 69.00 | 68600 |
| 5 | Ket' (Bol'shaya Ket') at Rodionovka | Ob | 58.42 | 83.67 | 71500 |
| 6 | Severnaya Sosva at Igrim | Ob | 63.18 | 64.40 | 87800 |
| 7 | Chulym at Baturino | Ob | 57.78 | 85.15 | 131000 |
| 8 | Ob at Barnaul | Ob | 53.40 | 83.82 | 169000 |
| 9 | Tobol at Yalotorovsk | Ob | 56.67 | 66.35 | 241000 |
| 10 | Ob at Kolpashevo | Ob | 58.30 | 82.88 | 486000 |
| 11 | Irtish at Omsk | Ob | 55.02 | 73.30 | 769000 |
| 12 | Ob at Belogor'e | Ob | 61.07 | 68.60 | 2690000 |
| 13 | Ob at Salekhard | Ob | 66.63 | 66.60 | 2950000 |
| 14 | Taseeva at Mashukovka | Yenisei | 57.82 | 94.32 | 127000 |
| 15 | Podkamennaya Tunguska at Kuz'movka | Yenisei | 62.32 | 92.12 | 218000 |
| 16 | Yenisei at Bazaikha | Yenisei | 55.98 | 92.80 | 300000 |
| 17 | Selenga at Novoselenginsk | Yenisei | 51.10 | 106.67 | 360000 |
| 18 | Selenga at Raz'ezd Mostovoy | Yenisei | 52.03 | 107.48 | 440000 |
| 19 | Angara at Boguchany | Yenisei | 58.38 | 97.45 | 866000 |
| 20 | Yenisei at Yeniseisk | Yenisei | 58.45 | 92.15 | 1400000 |
| 21 | Yenisei at Podkamennaya Tungus | Yenisei | 61.60 | 90.08 | 1760000 |
| 22 | Yenisei at Igarka | Yenisei | 67.43 | 86.48 | 2440000 |
| 23 | Chara at Tokko | Lena | 60.00 | 119.88 | 62500 |
| 24 | Olekma at Kudu-Kel' | Lena | 59.37 | 121.32 | 115000 |
| 25 | Vilyuy at Suntar | Lena | 62.15 | 117.65 | 202000 |
| 26 | Aldan at Ust'-Mil' | Lena | 59.63 | 133.03 | 269000 |
| 27 | Lena at Krestovskoe | Lena | 59.73 | 113.17 | 440000 |
| 28 | Vilyuy at Khatyrik-Khomo | Lena | 63.95 | 124.83 | 452000 |
| 29 | Aldan at Verkhoyanskiy Perevoz | Lena | 63.32 | 132.02 | 696000 |
| 30 | Lena at Tabaga | Lena | 61.83 | 129.60 | 897000 |
| 31 | Lena at Kusur | Lena | 70.68 | 127.39 | 2430000 |

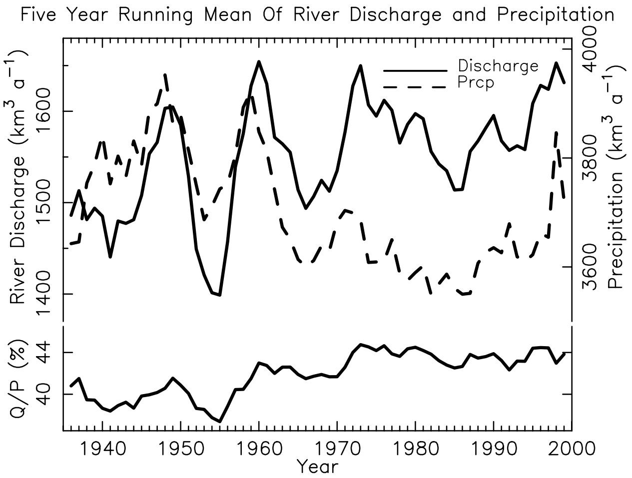

**Figure 3.** (top) River discharge and precipitation for the combined OYL basins, with a 5 year running mean filter applied. (bottom) Discharge/precipitation (Q/P) ratio. Discharge for the Yenisei at Igraka and the Lena at Kusur is reconstructed (see section 2) to eliminate the effects of large dams. River discharge for the Ob is taken from the R-ArcticNet archive (http://www.r-arcticnet.sr.unh.edu/). Precipitation is interpolated from TD9813 station records and averaged across the EASE-Grid cells falling within the OYL basins.

further complicate interpretation of seasonal and annual discharge changes [*Yang et al.*, 2004b]. These human influences, however, are mostly confined to the upstream reaches of the basin. Section 6 further addresses the effect of reservoirs on the interpretation of trends.

[14] Changes in annual and seasonal discharge for the combined flow of the OYL are examined in a trend analysis for multiple time intervals over the 1936–1999 period. Seasonal discharges are defined by summing flows over winter (November–March), spring (April–June), and summer/fall (July–October). Basin average trends in CSP are estimated as follows. First, monthly TD9813 precipitation is interpolated to the nodes of the 25 × 25 km Equal Area Scalable Earth Grid (EASE-Grid) [*Brodzik and Knowles*, 2002]. Spatial averages of CSP each year from 1966 to 1995 are then calculated by integrating over the EASE-Grid cells falling within a given river basin/subbasin. Trends in CSP are calculated by linear least squares regression. The interpolation scheme is an inverse-distance-weighted method [*Shepard*, 1968]. Statistical significance of the linear trend is determined using the Mann-Kendall test for monotonic trend [*Mann*, 1945; *Kendall*, 1975], which has become increasingly popular in Arctic hydrological analysis [*McClelland et al.*, 2006; *Pavelsky and Smith*, 2006]. Our test for temporal autocorrelation using the Durban-Watson (DW) statistic suggests that there is little influence among the annual and seasonal discharges or CSP time series. Trends are considered significant when the p value from the Mann-Kendall test is less than the critical value $p < 0.2$ (80%) in the analysis in sections 3 and 5. Analysis of the in situ meteorological station data (section 4) involves a critical value of $p < 0.1$ (90%) to identify significant precipitation-based trends. Significance of Pearson product-moment correlations are assessed using the t distribution and a confidence level of 95%.

## 3. Trends in Annual and Seasonal River Discharge

[15] Annual and seasonal discharge for the combined flow from the Ob, Yenisei, and Lena basins (OYL) are examined here to better understand the driving mechanisms for the reported long-term increase from northern Eurasia. As mentioned above, our analysis includes a reconstructed record for the Yenisei at Igarka and the Lena at Kusur to reduce the influence of the impoundments. Similar to the trend across the six basins [*Peterson et al.*, 2002], river discharge for the aggregate flow from the OYL basins increased over the period 1936–1999 (Figure 3). Although no trend in annual precipitation emerges when individual basins are examined, aggregate precipitation across the OYL region declined based on a linear fit to the data. But as seen in Figure 3, neither time series exhibits a monotonic trend. Over the period 1936–1999 the correlation coefficient (prewhitened, water year totals) is 0.59. However, for the period up to 1970, the correlation is 0.77. Thereafter, particularly from the mid-1960s to the mid-1990s, annual precipitation values are lower and, more importantly, discharge/precipitation ratios are higher. A similar pattern was noted for the entire Eurasian6 basins [*Rawlins et al.*, 2006], which is not unexpected, as the OYL region comprise roughly 87% of the area of the Eurasian6.

[16] Figure 4 shows annual and seasonal trends (significant at $p < 0.2$) for the combined OYL discharge in a multiperiod analysis. As previously mentioned, this type of analysis provides a more robust representation of change given the sensitivity of trends estimates to choice of start and end years. Discharge in winter, i.e., November–March, shows an acceleration in recent decades, with a high prevalence of greater trends for time intervals beginning in the late 1960s. Given our use of reconstructed discharge for the Yenisei at Igarka and Lena at Kusur, natural causes are likely involved in this acceleration of winter discharge. This result is supported by rises in minimum daily flows (which mostly occur during winter) which have been reported for small to medium-sized rivers with an absence of dams across northern Eurasia [*Smith et al.*, 2007]. Similarly, positive trends are noted for the combined flow during spring. The significance of the spring trends are generally lower than those for other periods shown in Figure 4. The number of time periods with significant spring trends are also fewer than with winter discharge, and no trend is present over the earlier decades. Spring trend magnitudes of approximately 0.7 to 1.5 $km^3 a^{-2}$, interestingly, are no greater, in general, than the winter trends. Winter flows are a fraction of those observed during spring, which implies a larger increase in winter relative to the winter mean. River discharge across Eurasia is largely driven by the seasonal accumulation of snow storage and its subsequent melt and runoff processes. Over the 60 year period from 1936 to 1995, spring (AMJ) discharge, on average, comprises approximately 50% of the annual flow from the Ob, Yenisei, and Lena basins. The presence of frozen soils or a shallow active layer limits infiltration of runoff and result in high runoff/precipitation ratios. Thus,

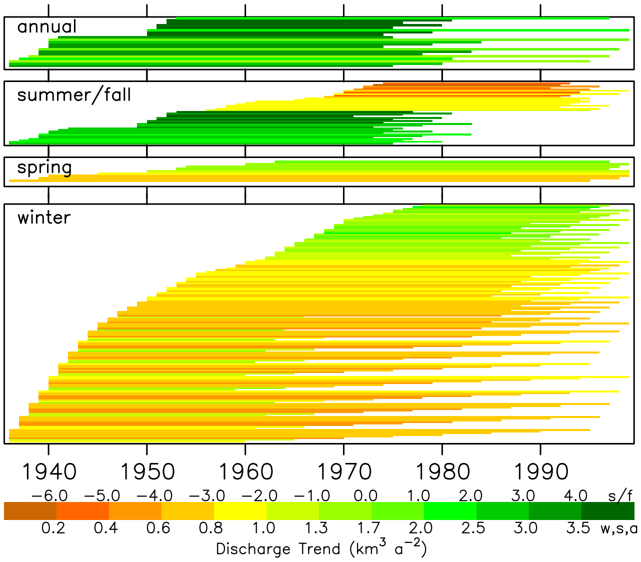

**Figure 4.** Annual and seasonal river discharge trends, for the combined flow of the OYL basins, for all periods with a significant trend ($p < 0.2$). The extent of each rectangle denotes the period over which the trend extends, while the color indicates the slope magnitude. Seasons are winter (November–March), spring (April–June), and summer/fall (July–October). The break points for summer/fall trends are shown above the color bar (s/f), with breakpoints for winter, spring, and annual trends (w, s, a) indicated by values below the color bar.

any significant changes during spring carry the potential to strongly influence annual discharge totals. In sharp contrast to the positive trends in winter and spring, which are never negative, summer/fall discharge exhibits a pattern of positive trends for several periods in the earlier decades, and negative trends over the most recent ones (Figure 4). For the period roughly from 1970 to the mid-1990s, the decreases approaches $-5$ km$^3$ a$^{-2}$, exceeding the positive trends for any other season or time period.

[17] Annual discharge trends, like those during spring, are positive for several of the longest (50+ years) periods (Figure 4). Across the OYL basins, 50+ year trends are generally positive and significant, approximately 1 to 1.5 km$^3$ a$^{-2}$ ($\sim$0.12 to 0.18 mm a$^{-2}$) (Figure 4). This suggests that the discharge increase from the OYL constitutes a large fraction ($\sim$75%) of the trend from the entire Eurasian6. The strongest trends, however are noted for several periods beginning around 1950. Such positive trends can also be seen by examining the nature of the time series shown in Figure 3. While trend estimates for time periods starting in the mid-1950s to mid-1960s are most sensitive to the influence of dam filling, which began around that time for many reservoirs [*Adam et al.*, 2007], our results suggest that the positive annual trends are largely explained by positive trends in summer/fall discharge. Soon thereafter, spring and winter discharge trends increase and summer/fall trends decrease.

## 4. Geography of Seasonal Precipitation Trends

[18] Recent studies have suggested that winter precipitation has been increasing over northern Eurasia in recent decades [*Ye et al.*, 1998; *Frey and Smith*, 2003; *Ye and Ellison*, 2003]. Precipitation which occurs during the cold season in the Arctic, particularly over regions of permafrost or seasonally frozen ground, carries a greater potential to influence river discharge than does precipitation across more temperate regions or which falls during other times of the year. Snowmelt on ground that is frozen or has a shallow thawed zone tends to produce runoff, rather than infiltrate the soil. Precipitation during summer is often recycled within these river basins [*Serreze et al.*, 2002]. Aggregate annual discharge from the OYL has a significant and positive relationship with cold season (October–April) precipitation (Figure 5). This comparison suggests that seasonal snow accumulation in this region influences not only the spring runoff period, but annual total discharge over the year as well.

[19] Over the period 1966–1995, positive trends ($p < 0.1$) in cold season (October–April) precipitation are noted across the central Ob, northern Yenisei, and western and northern Lena basins (Figure 6a). Twenty-five of the 325 stations ($\sim$8%) exhibit increases, while 23 ($\sim$7%) show decreases (Table 2). Relatively equal numbers of significant positive and negative trends in maximum daily discharge have also been noted across the Russian Arctic drainage basin [*Shiklomanov et al.*, 2007]. Positive CSP trends outnumber negative trends in the Ob and Lena basins, with a large concentration of positive trends across the central portion of the Ob basin. Although we examine here the number of stations with positive and negative trends, it should be mentioned that the net effect of precipitation is largely a reflection of the magnitude of the trends within a given watershed. Regionally coherent patterns of CSP increases, largely devoid of negative trends, are present across the central Ob basin, the northern Yenisei basin, and the northern and western parts of the Lena basin. In contrast

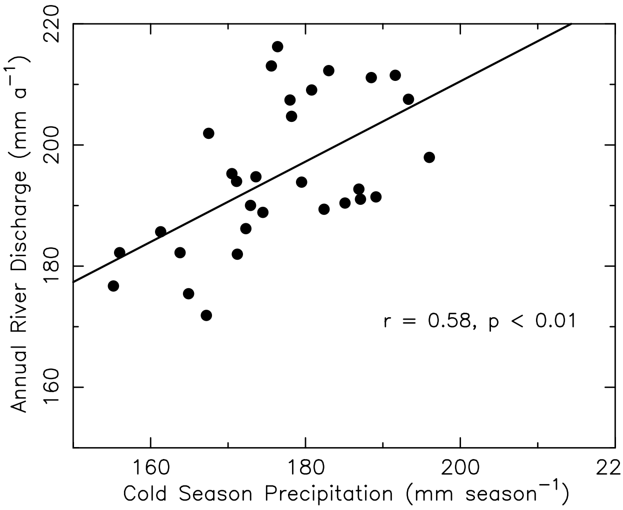

**Figure 5.** Annual river discharge (mm a$^{-1}$) averaged across the OYL basins versus cold season (October–April) precipitation (CSP) over the same region, 1966–1995. CSP is calculated from TD9813 precipitation data and interpolated to the EASE-Grid prior to spatial averaging. Annual discharge is converted to a unit depth runoff. Linear least squares fit is shown.

to the positive trends across northern Eurasia, decreasing CSP is apparent to the south. Stations for which CSP has a significant negative trend are found in three regions: the southeastern Ob, the southern Yenisei, and the eastern Lena. For the Lena basin significant declines in CSP and snow depth are noted primarily across the southeast within the Aldan subbasin.

[20] Observations of snow depth and snow water equivalent (SWE) have been gathered throughout the former USSR since the early 1900. There are 71 stations which have sufficient data for trend analysis. Snow depths increased at 13 stations and decreased at only 5 stations (Table 2). Spatially, trends in snow depth are broadly consistent with trends in CSP totals (Figures 6a and 6b). The positive trends are also consistent with previous research documenting increasing snow depths over northern Russia and decreasing depths across southern Russia between 1936 and 1983 [*Ye et al.*, 1998; *Groisman et al.*, 2006]. Any assumption of a correlation between increasing snow depth and increasing river runoff is dependent on information on snow densities over time. In the absence of evidence suggesting a trend toward lower snow densities, the increasing snow depths, in general, support the notion that cold season precipitation increased across northern Eurasia over the 1966–1995 period.

[21] Direct in situ observations of SWE are largely absent across far northern Eurasia. There are, however, areas where winter precipitation trends agree, in general pattern, with the SWE trends. These regions are the central Ob basin (positive trends) and the southern Yenisei basin (negative trends). Within the OYL, increases in January–March average SWE are found at 25 of the 179 (~14%) stations, almost exclusively over the Ob basin. Only 4 stations show a decreasing trend, with three of those stations located across the extreme southern Yenisei basin. The spatial pattern in CSP, snow depth, and SWE trends (Figure 6c) shows general agreement across the central Ob basin.

[22] Significant change in seasonal precipitation is not confined to the cold season. From 1966 to 1995, total precipitation over the months of June–August decreased

**Table 2.** Number of Stations With a Significant Positive (Negative) Trend in CSP[a]

| | Basin | | | |
|---|---|---|---|---|
| | Ob | Yenisei | Lena | OYL |
| CSP | 16 (7) | 4 (13) | 5 (3) | 7.7 (7.1) |
| Snow depth | 8 (1) | 2(1) | 3 (3) | 18.3 (7.0) |
| SWE | 22 (1) | 0 (3) | 3 (0) | 14.0 (2.2) |

[a] Significance is p < 0.1. From TD9813, snow depth, and SWE (both from Former Soviet Union Hydrological Snow Surveys [*Krenke*, 1998] within the Ob, Yenisei, and Lena basins. The associated percentages for the combined OYL region are shown in parentheses.

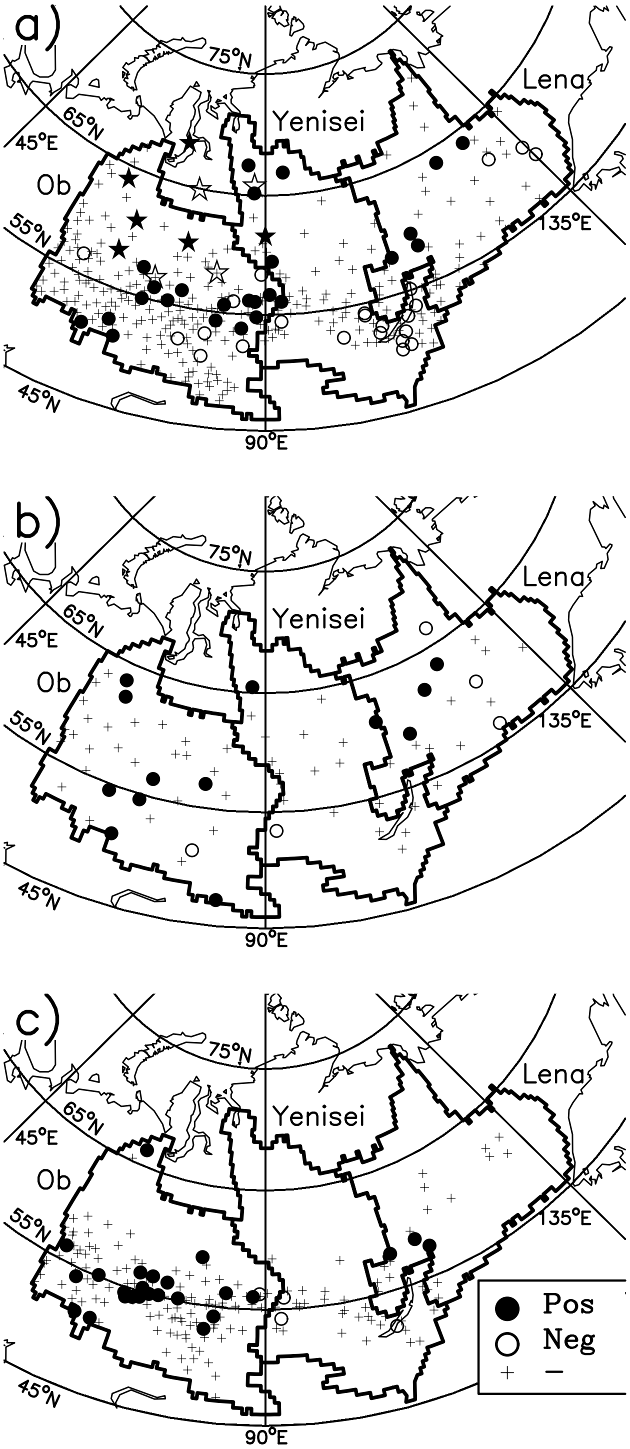

**Figure 6.** (a) Stations with a trend (positive and negative) in CSP for the period 1966–1995. CSP, taken from TD9813 station records, is calculated as the total over the months October–April. The nonparametric Mann-Kendall test is used to determine statistical significance. Statistics are determined for all stations within the OYL with at least 15 years with no missing data during October–April. Large filled circles show locations of stations with a positive trend significant at p < 0.1. Open circles mark the stations with a significant negative trend. Stations with no significant trend are denoted with a plus. Locations of stations examined by *Frey and Smith* [2003] are marked by stars, with stations showing a positive winter precipitation trends (4) represented with open stars and the other 6 stations indicated with filled stars. (b) Same as Figure 6a for trend in annual average snow depth. (c) Same as Figure 6a for trend in January–March average snow water equivalent (SWE).

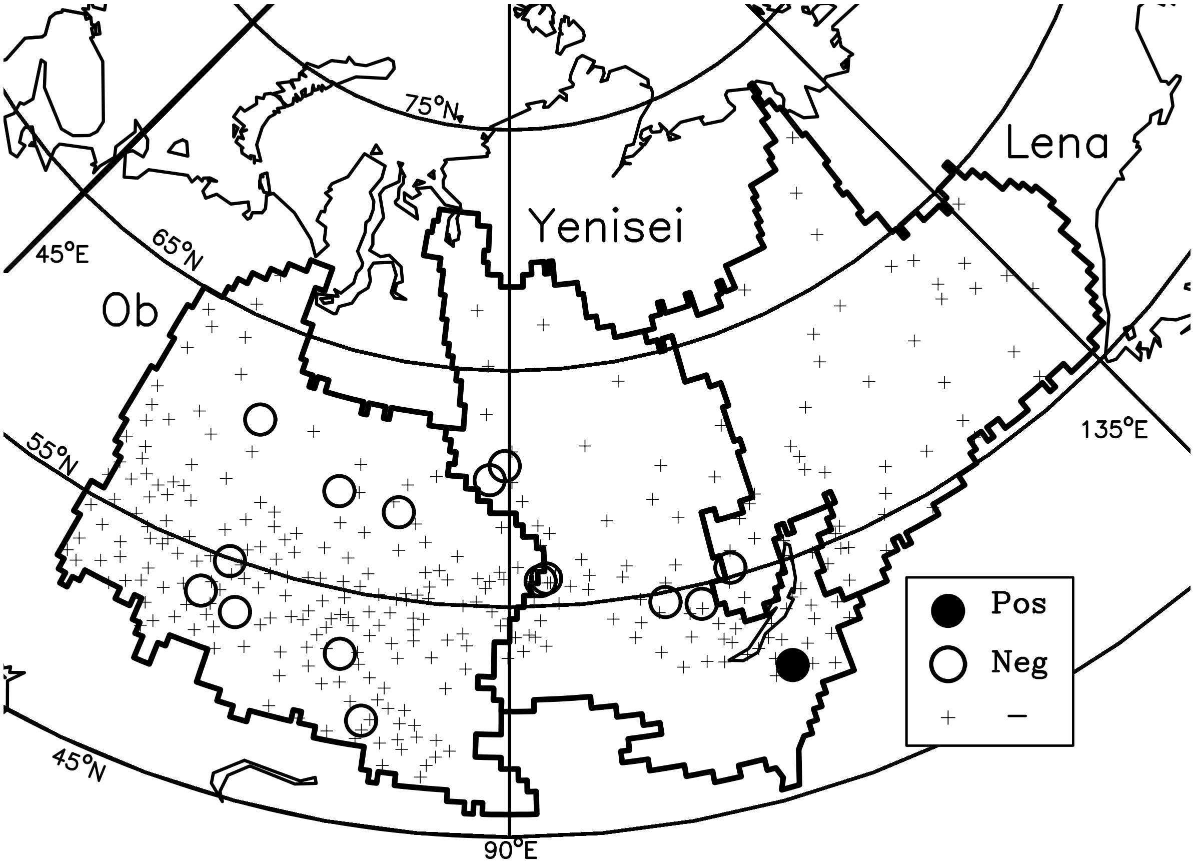

**Figure 7.** Same as in Figure 6 except for trend in June–August precipitation.

across much of OYL basins (Figure 7). Among 329 stations with sufficient data we note negative trends at 15 stations and positive trends at only one station. Examining total precipitation over the months of May–September we observe negative trends at 16 stations and positive trends at only 2, with a nearly identical spatial pattern (not shown). Negative trends are most prevalent across the Ob basin. While occurring over a shorter period of time, rainfall typically constitutes the majority of annual total precipitation over much of northern Eurasia. Although our analysis of the station-based precipitation trends involves the period 1966–1995, these negative trends in June–August precipitation, when considered with the mostly positive CSP trends, largely explain the reported finding of no trend in annual precipitation averaged across the OYL region over the period 1936–1999 [*Berezovskaya et al.*, 2004].

## 5. Precipitation and Discharge Trends Across Subbasins of the OYL

[23] Trends in CSP and spring discharge among the 31 subbasins for the period 1966–1995 are shown in Figure 8. Significant ($p < 0.2$) trends (both positive and negative) in spring discharge are noted for only 7 of the 31 subbasins (Table 3). When the linear slope in CSP (not all of the subset subbasins have significant CSP trends) and spring discharge are compared, no significant correlation between the trends emerges (Table 4). A large disagreement is noted

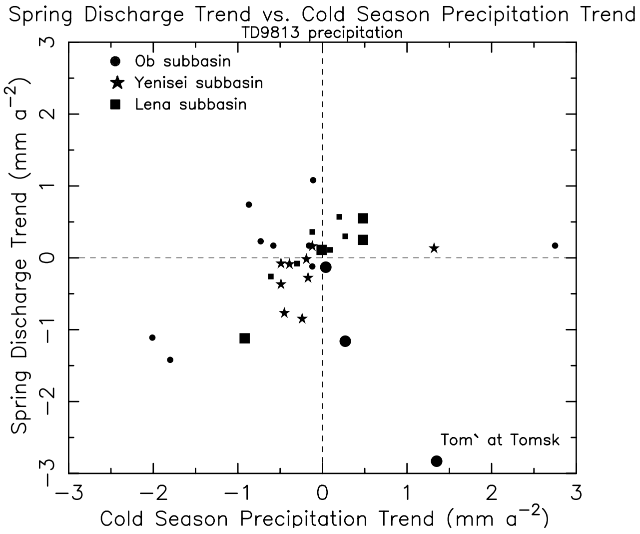

**Figure 8.** Trend in spring discharge versus trend in CSP (Table 3), both in mm season$^{-2}$, for the 31 subbasins of the OYL. The CSP totals are from TD9813 data. Subbasins of the Ob, Yenisei, and Lena are shown with circles, stars, and squares, respectively. Large symbols denote the seven subbasins with a significant trend ($p < 0.2$) in spring discharge.

**Table 3.** Mean Precipitation P and Spring Discharge Q, Standard Deviation, and Trend Over the Period 1966–1995[a]

| Index | Station Name | MeanP | SDP | MeanQ | SDQ | TrendP | TrendQ |
|---|---|---|---|---|---|---|---|
| 1 | Tom' at Tomsk | 349.5 | 50.1 | 407.9 | 89.7 | 1.35 | **−2.83** |
| 2 | Katun' at Srostky | 190.3 | 37.6 | 166.9 | 30.8 | **−2.01** | −1.11 |
| 3 | Tura at Tumen' | 204.6 | 43.8 | 78.2 | 35.9 | −0.11 | 1.08 |
| 4 | Konda at Altay | 217.0 | 39.1 | 53.8 | 11.6 | −0.16 | 0.17 |
| 5 | Ket' (Bol'shaya Ket') at Rodionovka | 240.6 | 28.3 | 87.3 | 28.3 | **−0.87** | 0.74 |
| 6 | Severnaya Sosva at Igrim | 238.8 | 41.8 | 142.2 | 27.1 | −0.73 | 0.23 |
| 7 | Chulym at Baturino | 287.9 | 43.5 | 115.6 | 25.8 | **2.75** | 0.17 |
| 8 | Ob at Barnaul | 239.1 | 38.1 | 145.8 | 31.1 | **−1.80** | −1.42 |
| 9 | Tobol at Yalotorovsk | 177.0 | 35.7 | 9.8 | 6.7 | −0.58 | 0.17 |
| 10 | Ob at Kolpashevo | 263.8 | 29.4 | 123.0 | 23.1 | 0.27 | **−1.16** |
| 11 | Irtish at Omsk | 170.4 | 20.0 | 16.0 | 2.9 | 0.04 | **−0.13** |
| 12 | Ob at Belogor'e | 207.7 | 20.9 | 46.0 | 5.5 | −0.12 | −0.12 |
| 13 | Ob at Salekhard | 212.0 | 21.1 | 47.3 | 5.5 | −0.12 | 0.16 |
| 13 | Ob at Salekhard | 212.0 | 21.1 |  |  |  |  |
| 14 | Taseeva at Mashukovka | 135.4 | 24.3 | 93.5 | 21.3 | −0.24 | −0.85 |
| 15 | Podkamennaya Tunguska at Kuz'movka | 205.4 | 25.7 | 161.0 | 27.3 | **1.32** | 0.13 |
| 16 | Yenisei at Bazaikha | 133.5 | 21.3 | 86.9 | 34.1 | −0.45 | −0.77 |
| 17 | Selenga at Novoselenginsk | 93.8 | 15.2 | 19.8 | 4.5 | −0.19 | −0.02 |
| 18 | Selenga at Raz'ezd Mostovoy | 90.3 | 14.0 | 20.7 | 5.4 | −0.39 | −0.09 |
| 19 | Angara at Boguchany | 108.2 | 14.2 | 39.8 | 5.4 | **−0.49** | −0.08 |
| 20 | Yenisei at Yeniseisk | 122.7 | 16.9 | 61.9 | 9.6 | −0.49 | 0.37 |
| 21 | Yenisei at Podkamennaya Tungus | 145.1 | 16.0 | 87.0 | 10.6 | −0.17 | −0.28 |
| 22 | Yenisei at Igarka | 167.8 | 13.6 | 124.4 | 14.6 | 0.27 | 0.30 |
| 23 | Chara at Tokko | 105.6 | 14.0 | 150.9 | 29.7 | −0.30 | −0.08 |
| 24 | Olekma at Kudu-Kel' | 101.0 | 16.7 | 121.5 | 36.6 | −0.12 | 0.36 |
| 25 | Vilyuy at Suntar | 142.7 | 17.7 | 44.8 | 17.1 | 0.48 | **0.55** |
| 26 | Aldan at Ust'-Mil' | 154.4 | 21.7 | 162.8 | 29.6 | **−0.69** | −0.26 |
| 27 | Lena at Krestovskoe | 120.6 | 14.6 | 133.8 | 17.2 | 0.20 | 0.57 |
| 28 | Vilyuy at Khatyrik-Khomo | 130.0 | 14.2 | 50.1 | 17.7 | 0.48 | **0.25** |
| 29 | Aldan at Verkhoyanskiy Perevoz | 131.7 | 16.5 | 117.8 | 23.9 | **−0.92** | **−1.12** |
| 30 | Lena at Tabaga | 125.4 | 12.7 | 108.9 | 17.3 | 0.09 | 0.11 |
| 31 | Lena at Kusur | 133.2 | 8.5 | 92.7 | 15.2 | −0.01 | **0.11** |

[a] MeanP, MeanQ, in mm season$^{-1}$; SDP, SDQ, standard deviation, in mm season$^{-1}$; and TrendP, TrendQ, trend, in mm season$^{-2}$. For the 31 subbasins listed in Table 1. Bold values indicate trends which are marginally significant ($p < 0.2$).

for the Tom' at Tomsk in the southern Ob basin. The Ob basin, like the Yenisei, contains several large reservoirs [*Yang et al.*, 2004a]. However, none are located on the Tom tributary. We are unaware of a reason for this large discrepancy. Eliminating the data point from the comparison results in an improved correlation ($R^2$ = 0.39) which also falls below the critical value ($R^2$ >0.53 for N = 6). When the subbasins of the Ob are excluded, the agreement in trends improves ($R^2$ = 0.95). This comparison, however, involves only four subbasins of the Lena basin.

[24] Agreements between CSP trends and spring discharge trends are also assessed using gridded precipitation from the Willmott-Matsuura (WM) archive to produce basin average CSP and the associated trends. In this case (Figure 9) the agreement between trends is generally higher; $R^2$ = 0.57(0.90) when the 7(6) subbasins described above are examined. The agreement is also better ($R^2$ = 0.92) for the four Lena subbasins with a significant discharge trend. This suggests that trends in CSP from WM data explain approximately 92% of the variance in spring discharge trends across those subbasins. Agreements with WM data are consistent with a recent study which showed that, among four different precipitation data sets, trends in annual

**Table 4.** Average Correlation R and Explained Variance $R^2$ Between CSP Trend and Spring Discharge Trend[a]

|  | TD9813 |  | WM |  |
|---|---|---|---|---|
|  | R | $R^2$ | R | $R^2$ |
| OYL | −0.35 | 0.12 | 0.76 | 0.57 |
| OYL-Tom | 0.62 | 0.39 | 0.95 | 0.90 |
| Lena | 0.97 | 0.95 | 0.96 | 0.92 |

[a] CSP trend derived from TD9813 and WM data. Correlation is between (1) the seven subbasins of the OYL with a significant trend in spring discharge, (2) the six subbasins remaining when the Tom' at Tomsk is removed from the comparison, and (3) the four Lena subbasins with a significant trend.

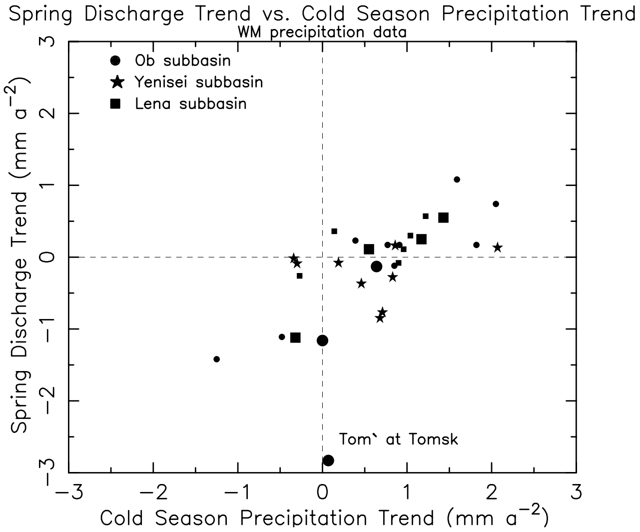

**Figure 9.** Same as in Figure 8 but with CSP calculated from monthly precipitation in the Willmott-Matsuura archive (Willmott and Matsuura, 2001).

precipitation computed from WM grids were found to agree most favorably with trends in river discharge among a collection of 198 Eurasian river basins (151 to 897,000 km$^2$) free from the influence of dams [*Pavelsky and Smith*, 2006]. The difference in results between trends in CSP produced from our interpolations of TD9813 precipitation and from the WM data likely arises because of at least two reasons. First, adjustments for biases such as gauge undercatch are part of the TD9813 archive. The WM data archive was produced through interpolation of raw gauge data records. Second, our method of interpolating the TD9813 precipitation data (see section 2) differs slightly from that used to generate WM data in that we use fewer nearby neighbors (4–10, average of 7). Put another way, the quality of gridded precipitation fields can substantially influence the agreement between river discharge and precipitation across the terrestrial Arctic [*Pavelsky and Smith*, 2006]. Despite the good correlations with WM data it is possible that the Pearson correlation coefficient is likely to have overestimated the true strength of the relationship given the small number of subbasins in the regressions.

## 6. Discussion and Conclusions

[25] Previous studies have documented increases in solid precipitation measures across northern Eurasia [*Ye et al.*, 1998; *Frey and Smith*, 2003; *Groisman et al.*, 2006], consistent with modeling studies which suggest increases in winter precipitation as a result of warming [*Kattsov et al.*, 2007]. From the beginning of discharge observations in the late 1930s until roughly 1970, annual discharge from the OYL basins correlates well with annual precipitation. It is thereafter that discharge rates are consistently higher, and annual precipitation is much lower, than in previous decades. The significant relationship between CSP and annual river discharge for the OYL (Figure 5) suggests that seasonal snow accumulation influences basin hydrology beyond the spring melt period.

[26] The results suggest that winter and spring discharge from the OYL region increased over the period 1966–1995 (Figure 4). As previous research has documented, most of the increasing winter trend contained within the raw discharge records is attributable to the influence of dams. Our use of reconstructed time series for the Yenisei and Lena basins removes these unwanted influences. While we have not accounted for the effects of dams across the Ob basin, our results, when considered together with other recent research, suggest that natural causes may be largely responsible for the winter and spring flow increases. Examining a collection of 138 small to medium-sized unregulated rivers in northern Eurasia, *Smith et al.* [2007] reported increases in minimum daily flows (which mostly occur during winter), with a greater rise in minimum flow over the period 1958–1989 relative to 1936–1999. Moreover, *Adam et al.* [2007], examining two separate reconstructed discharge products, found that while one accounted for most or all of the change in January through March discharge, the second product accounted for between 21% and 48% of the trend. Another study found that the discharge increase observed at the mouth of the Lena basin is likely a result of the combined effect of reservoir regulation and natural runoff changes in the unregulated upper subbasins [*Ye et al.*, 2003]. Nonetheless, direct linkages between increasing CSP and increasing winter discharge are not easily made, as winter precipitation tends to accumulate on the surface with little melt occurring until spring thaw. Other processes may also be involved. A recent study which describes positive trends in winter base flow from rivers in the Canadian Northwest Territories points to increased permafrost thawing, and the authors have speculated that enhanced infiltration and deeper flow paths are the primary mechanism [*St. Jacques and Sauchyn*, 2009]. Spring discharge from the OYL region has also accelerated, with trend magnitudes similar to those noted in winter. High intrinsic variability in these spring discharge totals, however, contributes to a lower statistical significance of their trends. Previous research suggests that they may be real, and likely to have a largely natural origin. In their analysis of reconstructed discharge products, *Adam et al.* [2007], suggested that while dams may account for much of the early spring (March and April) trends, their influence on May flows is negligible. They also indicated that spring flows exhibited increases for periods starting in the 1950s and 1960s and ending in the 1990s. Other work has also suggested that reconstructed monthly flows have higher trends during most of the high flow months, with the higher monthly trends transferring into a higher trend in annual flow [*Ye et al.*, 2003]. In other words, dams may be reducing what would be the natural trend in annual river discharge from these large Eurasian rivers.

[27] In contrast to the nature of winter and spring trends, summer/fall discharge from the OYL basins increased for roughly the first three decades, and then sharply declined during the last three. The decline in summer/fall discharge over the latter decades (1965–1995) is concurrent with decreases in summer precipitation, most notable across the Ob basin (Figure 7). *Smith et al.* [2007] also found decreases in minimum daily flows in summer (1958–1989) from small, unregulated basins. This summer drying is consistent with a positive trend in 500 hPa height anomalies across much of northern Eurasia between 1960 and 1999 [*Serreze et al.*, 2002]. The change in summer/fall discharge trends with time reveals much about the annual trends. Increases in annual discharge over the earliest decades, when the precipitation-discharge correlation is highest, align with trends in summer/fall discharge. Although it is reasonable to assume that much of the variability in summer/fall discharge is driven by variations in summer/fall precipitation, we find that correlations between the two across the OYL basins during the earlier decades are not particularly strong. This suggests that variations in evapotranspiration or changes in storage are also important during summer. Sharp declines during the latter decades offset the winter and spring increases, and annual trends are largely absent over the more recent decades. Examining reconstructed discharge for these basins individually, *Adam and Lettenmaier* [2008] suggested that annual flows have accelerated for both the Lena and Yenisei basins, but not for the Ob, with the largest positive trends noted for the latter part of the record, starting around the early 1970s. Our results are consistent with those findings, as the large decreases in summer/fall discharge from the Ob basin described here would tend to offset, to some degree, the annual increases from the Yenisei and Lena basins. It must be said that one would not expect many of the seasonal

trends for the individual basin to be significant. While analyzing annual discharge for the Eurasian6 basins, *Peterson et al.* [2002] emphasized that long-term trends for the individual rivers can be difficult to detect given the high interannual variability expressed by these rivers, and it is only when the flows are summed across the large region that a significant signal emerges. Similarly, divergent trends become most evident when seasonal discharge for the combined flow of the OYL is examined (Figure 4). Although much uncertainty exists in estimating regional-scale water budgets, it is apparent that a divergence in seasonal flows occurred during the latter decades of the period from 1936 to 1999.

[28] Our examination of CSP trends at the meteorological stations provides important insights into the role of solid precipitation increases as a mechanism behind the long-term discharge trends. The geography of CSP trends is important to note, particularly across northern high latitude regions. Permafrost is most extensive across the Lena basin and northern Yenisei, with sporadic or discontinuous permafrost present across the Ob basin [*Brown et al.*, 2001; *Ye and Fetzer*, 2009]. Snowmelt on frozen soil results in a greater proportion of the snowpack water reaching rivers. Increases in precipitation across southern headwaters is inherently less influential with respect to the observed discharge trends at the downstream sites. Moreover, rainfall during the warm season is subject to significantly greater infiltration into soils when the active layer develops in permafrost regions, or seasonally frozen ground thaws in nonpermafrost locations. Across the three-basin region, both positive and negative CSP trends are observed. The Ob basin is characterized by a large number of stations which experienced increased CSP, primarily across the central part of the basin. Of the 4 (out of 10) stations described by *Frey and Smith* [2003] with significant trends over 1958–1999, 2 are located within the Ob basin (Figure 6a, marked with open stars). Although increasing trends outnumber decreases here by more than 2 to 1, the influence of snowmelt on river runoff across the Ob is generally much lower than it is over the permafrost dominated Yenisei and Lena basins. Compared to the Yenisei and Lena, precipitation has less impact on the Ob River discharge given large storages in wetlands and ponds as well as greater losses through evapotranspiration, and hence lower runoff/precipitation ratios [*Serreze et al.*, 2002]. Ob basin evaporation has been shown to account for as much as 74% of annual precipitation over the basin [*Berezovskaya et al.*, 2004].

[29] Among the three basins, the Yenisei has perhaps the strongest gradient (south-to-north) in CSP trends. Significant CSP declines have occurred across the southern portion of the basin, while positive trends are evident to the north (Figure 6a). The presence of positive CSP trends across the northern Yenisei also helps to explain why basin discharge trends were found to be consistently more positive than annual precipitation trends [*Adam and Lettenmaier*, 2008]. Snow depth has also increased across the basin, and although we have no information suggesting that there have been systematic changes in snow density, it is reasonable to assume that the increases in snow depth are related to the positive trends in winter precipitation, its water equivalent, and river discharge over the region. Although decreases in solid precipitation may be related to warming, we cannot assume that a transition to more liquid precipitation would reduce precipitation totals during those months. Positive trends in CSP are also found over the western and northern Lena basin, with corresponding increases in snow depth and SWE across the western half of the basin.

[30] The comparisons of CSP and spring discharge trends, when considered in the context of the seasonal discharge changes (section 3) and spatial configuration of the station-based CSP trends (section 4), can be used to link CSP changes to the long-term annual discharge trends. Although the trend comparison shows marginal agreement across all OYL subbasins, the agreement noted when WM precipitation data are used suggests a linkage (Table 4). This is noteworthy given that previous research has suggested that much (∼75%) of the increase in annual river discharge over the longer period (1936–1999) analyzed by *Peterson et al.* [2002] was driven by positive trends in the Lena and Yenisei rivers [*Berezovskaya et al.*, 2004]. The period between 1966 and 1995 is characterized by increases in winter and spring discharge from the OYL basins, along with an increase in discharge/precipitation ratios. The CSP, snow depth, and SWE analysis suggests positive trends across the northern parts of the basins. Summer precipitation and summer/fall discharge declined over that same period. Although our study is an empirical investigation and does not include a full water budget analysis, the changes described here suggest that increased CSP can be connected with the annual discharge trend through the positive trends in spring discharge and, to a more limited extent, the winter discharge increases. While it has been suggested that positive streamflow trends which exceed annual precipitation trends suggest another source of water [*Adam and Lettenmaier*, 2008], we hypothesize that these lower annual precipitation trends are a result of decreases in summer precipitation together with increases in CSP and, moreover, that the positive trends in CSP are forcing spring discharge and, hence, annual discharge trends across northern Eurasia. These trends were previously reported for the Yenisei basin for the period 1960–1999 [*Serreze et al.*, 2002]. The precipitation-discharge connection is also evidenced by correlations between annual precipitation and annual discharge among a collection of the small unregulated basins across this region. Of the 40 basins displaying statistically significant trends in discharge, 29 were found to have corresponding trends in precipitation, with a 35–62% agreement between the trends [*Pavelsky and Smith*, 2006]. With our comparisons between CSP and spring discharge trends in mind, two caveats must be mentioned regarding factors that limit the robustness of the evaluations. The nested (smaller basins fall within larger ones) subbasins integrate river runoff processes across the watershed as the basin sizes grow moving downstream through the river system. Moreover, the physiography of the Ob basin (a low permafrost extent with an abundance of lakes and wetlands) limits the CSP runoff response much more than what we observed across the Lena basin. In some sense, one would be surprised to find strong correlations across the Ob basin.

[31] Trends in cold season and in summer precipitation drawn from the stations are consistent with changes sug-

gested in modeling studies [*Wu et al.*, 2005; *Kattsov et al.*, 2007]. These alterations, moreover, may continue into the future. *Finnis et al.* [2007] identified changes in cyclone-associated precipitation during winter across the northern high latitudes within ensemble runs of the NCAR CCSM3 which they attributed to an increase in atmospheric precipitable water in the model. The NH jet stream has shifted northward and its winds have increased during winter [*Archer and Caldeira*, 2008]. Atmospheric teleconnections influencing the discharge trends, however, are not entirely clear. Increases in high-latitude precipitation over time are generally expected to occur because of climate change and a warmer atmosphere. While additional precipitation was likely advected into central Eurasia during active phases of the North Atlantic Oscillation (NAO) and the related mode of sea level-pressure variability, the Arctic Oscillation (AO), during the 1980s and 1990s, natural atmospheric modes such as the Northern Annular Mode (NAM) have retreated to more neutral values during the past decade [*Serreze et al.*, 2006]. Moreover, the AO index was found to be linearly congruent with only 17% of the precipitation trends across West Siberia [*Frey and Smith*, 2003]. That said, the NAO and AO indices were found to have only limited use for analyzing climate impacts in river basins in northwest Europe [*Bouwer et al.*, 2008]. However, recent radical shifts north and eastward of the Icelandic low [*Zhang et al.*, 2008] should spur debate into whether the recent discharge increases are a manifestation of decadal-scale fluctuations like the AO, NAO or NAM, the effects of a warming atmosphere, or more likely, some combination of both. Given substantial decreases in sea ice across the Russian arctic [*Mahoney et al.*, 2008], an increase in the moisture flux from a more open ocean may be an additional moisture path responsible for the positive river discharge trends.

[32] Our analysis shows that the latter decades of the last century were characterized by a divergence in seasonal river discharge. Regardless of the sparsity of in situ observations and the precise magnitude and statistical significance of trends in snow-related measures, the trend analysis suggests that cold season precipitation changes across these basins can be linked with the annual discharge trends. That river discharge has risen so markedly despite sharp declines in summer precipitation is interesting, yet not surprising, and lends additional evidence that increased CSP may be the primary agent of change. In the few years since the increasing discharge from Eurasia was first identified, subsequent research has begun to unravel key aspects of the spatial and temporal character and drivers of this trend. Given projections of future increases in arctic precipitation, additional studies should focus on these recent changes in seasonal hydrology, the relevant drivers, processes, and feedbacks, and the linkages between the arctic water cycle and adjacent domains.

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