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Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean

Michael A. Rawlins
University of New Hampshire - Main Campus

C J. Willmot
University of Delaware

A Shiklomanov
University of New Hampshire - Main Campus, alex.shiklomanov@unh.edu

Ernst Linder
University of New Hampshire, ernst.linder@unh.edu

Steve Frolking
University of New Hampshire - Main Campus, steve.frolking@unh.edu

See next page for additional authors

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Authors
Michael A. Rawlins, C J. Willmot, A Shiklomanov, Ernst Linder, Steve Frolking, Richard B. Lammers, and Charles Vorosmarty

Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean

M. A. Rawlins,[1] C. J. Willmott,[2] A. Shiklomanov,[1] E. Linder,[3] S. Frolking,[1] R. B. Lammers,[1] and C. J. Vörösmarty[1]

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[1] To more fully understand the role of precipitation in observed increases in freshwater discharge to the Arctic Ocean, data from a new archive of bias-adjusted precipitation records for the former USSR (TD9813), along with the CRU and Willmott-Matsuura data sets, were examined for the period 1936–1999. Across the six largest Eurasian river basins, snowfall derived from TD9813 exhibits a strongly significant increase until the late 1950s and a moderately significant decrease thereafter. A strongly significant decline in derived rainfall is also noted. Spatially, snowfall increases are found primarily across north-central Eurasia, an area where the rainfall decreases are most prominent. Although no significant change is determined in Eurasian-basin snowfall over the entire 64 year period, we note that interpolation from early, uneven station networks causes an overestimation of spatial precipitation, and that the local snowfall trends determined from gridded TD9813 data are likely underestimated. Yet, numerous uncertainties in historical Arctic climate data and the sparse, irregular nature of Arctic station networks preclude a confident assessment of precipitation-discharge linkages during the period of reported discharge trends. **Citation:** Rawlins, M. A., C. J. Willmott, A. Shiklomanov, E. Linder, S. Frolking, R. B. Lammers, and C. J. Vörösmarty (2006), Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean, *Geophys. Res. Lett.*, *33*, L07403, doi:10.1029/2005GL025231.

1. Introduction

[2] Changes are occurring in the Arctic climate and hydrological cycles [*Serreze et al.*, 2000; *Peterson et al.*, 2002]. Increasing winter-average air temperatures [*Rawlins and Willmott*, 2003], reductions in sea-ice thickness and extent [*Serreze et al.*, 2003b], and a significant increase in river discharge of 0.22 mm yr^{-1} from 1936–1999 across Eurasia [*Peterson et al.*, 2002] have been documented. River discharge increases have the potential to impact global climate through alterations in the oceanic thermohaline circulation [*Rahmstorf*, 1995; *Broecker*, 1997]. Warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation, since precipitation increases will likely exceed evaporative losses [*Arctic Climate Impact Assessment*, 2005].

[3] With the potential for increased net freshwater input to the terrestrial Arctic, precipitation emerges as a likely source for the observed discharge trend. In a study of the possible effects of dams, melting of permafrost, and fires on river discharge, *McClelland et al.* [2004] suggested that increased precipitation is the most plausible source for the observed discharge trend. Annual total precipitation, however, has generally decreased across the three largest Eurasian basins since 1936 [*Berezovskaya et al.*, 2004]. Given this apparent disagreement between precipitation and river discharge, analysis of changes in seasonal precipitation is relevant to our understanding of the discharge trends. Indeed, increases in spring runoff across the Yenisey basin in central Eurasia during the period 1960–1999 have been linked with an increase in winter precipitation and earlier snowmelt [*Serreze et al.*, 2003a]. Acknowledging the challenges in deriving climate change signals from a sparse network of observations which contain numerous uncertainties, our study analyzes seasonal precipitation drawn from historical station data to better understand the role of precipitation in the river discharge increases from Eurasia.

2. Data and Methods

[4] Monthly station precipitation (P) time series are taken from NCDC's Dataset 9813, "Daily and Sub-daily Precipitation for the Former USSR" [*National Climatic Data Center*, 2005], which originated at the Russian Institute for Hydrometeorological Information-World Data Center of the Federal Service for Hydrometeorology and Environmental Monitoring, Obninsk, Russian Federation. Precipitation records in this archive (hereinafter TD9813) contain adjustments to account for wetting losses, i.e., moisture on the gauge walls, changes in gauge type and observing practices, and wind-induced errors (see TD9813 documentation and references therein). Among these inconsistencies, the undercatch errors due to aerodynamic effects of wind are generally greatest, particularly in winter [*Groisman et al.*, 1991]. Biases due to change in gauge type are also significant, while wetting losses are typically smallest. Bias adjustments are vital in order to accurately ascertain "true" changes in precipitation over time [*Yang et al.*, 2005; *Forland and Hanssen-Bauer*, 2000]. We also use monthly *P* and air temperature (*T*) data from the Willmott–Matsuura (WM) archive (C. J. Willmott and K. Matsuura, Arctic terrestrial air temperature and precipitation: Monthly and annual time series (1930–2000) version 1, http://climate.geog.udel.edu/~climate/, 2001) and from CRU v2.0 data

[1] Water Systems Analysis Group, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA.
[2] Center for Climatic Research, University of Delaware, Newark, Delaware, USA.
[3] Department of Mathematics and Statistics, University of New Hampshire, Durham, New Hampshire, USA.

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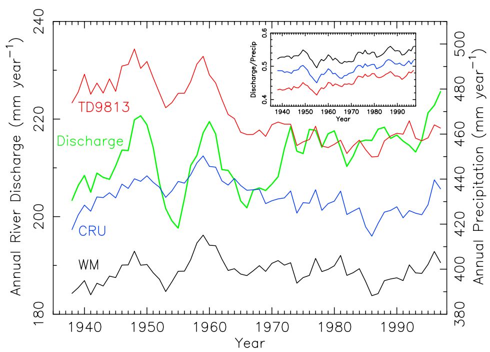

Figure 1. Five-year running means of spatially averaged river discharge (Q, mm yr^{-1}) and precipitation (P, mm yr^{-1}) across the 6 largest Eurasian river basins from 1936–1999. Inset shows the ratio of annual discharge to annual precipitation.

[*Mitchell et al.*, 2004]. Monthly P from TD9813 were interpolated to the 25 km $\times$ 25 km EASE-Grid using inverse-distance-weighted interpolation. CRU T and P at 0.5° $\times$ 0.5° resolution were sampled at each EASE-Grid. In contrast to the new TD9813 archive, CRU and WM data contain no adjustments for biases in the precipitation records. Spatial aggregations of the gridded data are made across the 6 largest Eurasian river basins; the Severnaya Divina, Pechora, Ob, Yenisey, Lena, and Kolyma. Annual snowfall (water equivalent) at each grid is calculated by examining T each month to estimate the fraction of monthly P as snowfall, and then summing those monthly snowfall amounts over the year. The ratio (R) of monthly snowfall to total monthly P is: $R = [1.0 + 1.61 \cdot (1.35)^T]^{-1}$, where T is the monthly mean in °C and $0 \leq R \leq 1$ [*Legates and Willmott*, 1990]. This function was derived using a logistic curve fit to monthly data and has a reported mean absolute deviation of 0.06 mm month^{-1}. Annual rainfall in a given year is totaled from the monthly amounts using $P \cdot (1 - R)$. River discharge (Q) records are drawn from an updated version of R-ArcticNET [*Lammers et al.*, 2001].

[5] Slope and significance from ordinary least squares regression are computed for spatially averaged annual rainfall across the Eurasian basin and for rainfall/snowfall at each EASE-grid over the region. A change-point regression method [*Draper and Smith*, 1981; *Müller et al.*, 1994] was applied for annual snowfall integrated over the Eurasian basin given the shape of the time series. This method determines optimal mid-series change-points by minimizing the sum of squared residuals of all possible change-point regressions. Serial autocorrelation was assessed graphically by plotting autocorrelation functions and numerically by calculating Durbin-Watson test statistics. Temporal correlations were not found at a 5% significance level.

[6] Potential biases in spatial P induced when gridding from irregular station networks was estimated by attempting to recreate total precipitation in 1972 using the available station networks each year from 1936–1999. In 1972 the station network was most dense, with 1549 and 341 stations having complete records across the former USSR and within the Eurasian basin, respectively. Starting from the 1972 station network, we sampled annual P at only those stations in operation each year for 1936, 1937 ... 1999. Those subsets of station P were then interpolated to the grids prior to spatial averaging across the Eurasian basin.

3. Linkages Between Precipitation and Discharge

[7] A significant correlation ($p < 0.01$) is noted among all three precipitation time series for the Eurasian basin (Figure 1). Annual precipitation is also correlated with annual discharge ($p \sim 0.05$ for TD9813), although the Pearson's correlation coefficient is low (r = 0.26, 0.41, 0.35, for TD9813, CRU, and WM respectively.) Correlations are not expected to be high given year-to-year changes in water storage over the landscape. The correlation over the period 1936–1970, however, is 0.55, 0.56, and 0.53, respectively. Thereafter, annual discharge increases yet precipitation declines. Discharge/precipitation (Q/P) ratios are highest between 1970–1990 (inset Figure 1).

[8] Estimating snowfall increases over northern lands is important, since snowmelt there occurs on frozen soils with low infiltration rates. A relatively small fraction of this water will evaporate and a larger proportion will run off. The ratio of runoff volume to snowmelt volume was found to have averaged 34% greater than the ratio for cumulative summer runoff and rainfall [*Kane et al.*, 2003]. Precipitation occurring during summer undergos considerably more recycling to the atmosphere and contributes more to soil recharge. It has been estimated that approximately 25% of July precipitation across northern Eurasia is of local origin [*Serreze et al.*, 2003a], i.e., associated with the recycling of water vapor within the domain.

[9] Annual snowfall derived from TD9813 precipitation exhibits a strongly significant increase (0.75 mm yr^{-1}) until the late 1950s followed by a moderately significant decrease (-0.30 mm yr^{-1}) thereafter (Figure 2 and Table 1). Strongly significant early increases (1.19, 0.96) are also noted for snowfall derived from CRU and WM, with insignificant decreases during the latter period. No significant change is noted in snowfall derived from TD9813 over the entire 1936–1999 period. The early snowfall increases derived

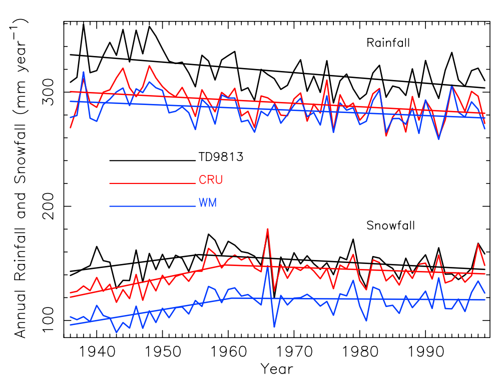

Figure 2. Spatially averaged water equivalent of annual rainfall and snowfall across the 6 largest Eurasian basins. Snowfall is derived using monthly gridded P data from TD9813, CRU, and WM data sets. Gridded monthly T is used to proportion monthly P to snowfall: $R = [1.0 + 1.61 \cdot (1.35)^T]^{-1}$, T is in °C and $0 \leq R \leq 1$ [*Legates and Willmott*, 1990]. Change-point regression [*Draper and Smith*, 1981; *Müller et al.*, 1994] is applied to the snowfall series. Annual rainfall is computed using $1 - R$.

Table 1. Trends in Annual *P*, Snowfall, and Rainfall Derived From TD9813, WM, and CRU *P* for 1936–1999[a]

	Annual P	Snowfall			Rainfall
Data Set	Trend, mm yr^{-1}	Trend1, mm yr^{-1}	Trend2, mm yr^{-1}	Change-Point, year	Trend, mm yr^{-1}
TD9813	−0.49[b]	0.75[b]	−0.30[c]	1955.5	−0.46[b]
CRU	−0.06	1.19[b]	−0.20	1960.5	−0.30[b]
WM	0.07	0.96[b]	−0.04	1959.5	−0.23[b]

[a]Trend1 and Trend2 are the change-point regression slopes for the early and late periods, respectively (see Figure 3a).
[b]Trends significant at $p < 0.01$.
[c]Trends significant at $p < 0.05$.

from CRU and WM precipitation are likely influenced by change in gauge type during the 1948–1953 period [*Groisman et al.*, 1991], and homogenization of the station records would tend to reduce the early trends. Such bias adjustments likely make the TD9813 data more representative of the true precipitation changes over time. It should also be noted that means and trends from CRU and WM are remarkably similar, despite differing methods used to grid the station data. Spatially, positive local trends drawn from the entire 1936–1999 period are noted primarily across north-central Eurasia, while negative trends occur across eastern Siberia (Figure 3a). These increases in derived snowfall are consistent with positive trends in winter *P* (4–13% decade^{-1}) across western Siberia [*Frey and Smith*, 2003] and snow depth across most of northern Russia [*Ye et al.*, 1998]. The geography of the snowfall changes is important to note, since they occur primarily across colder, northerly regions where soils have a limited capacity for infiltration during snowmelt.

[10] Consistent decreases in spatially averaged rainfall over the entire Eurasian basin have occurred (Figure 2). The magnitude of the rainfall decrease is greater than the snowfall increase (Table 1), consistent with the reported [*Berezovskaya et al.*, 2004] decline in total precipitation. Rainfall decreases are greatest across north-central Eurasia (Figure 3b), the area where positive snowfall trends are noted. A positive trend in 500 hPa height anomalies across much of northern Eurasia between 1960–1999 [*Serreze et al.*, 2003a] may be linked with the rainfall decrease during that time.

[11] Biases arising when interpolating from spatially uneven networks can be significant [*Willmott et al.*, 1994]. Station networks across Eurasia, for example, give rise to an overestimation of annual precipitation during earlier years (Figure 4). Early networks originated in the south and gradually expanded northward. Although true precipitation derived from the best Arctic networks is difficult, if not impossible, to know with certainty, we estimate a bias of well over +10 mm in the early network representations of spatial precipitation. A similar bias is noted when alternate base years are used. For assessments of continental-scale precipitation aggregations, early station networks essentially over-represent precipitation due to their uneven spatial arrangement.

4. Summary and Conclusions

[12] Annual precipitation across the Eurasian basin drawn from the gridded data are correlated with observed river discharge over the period 1936–1999. Annual discharge has become a larger fraction of total precipitation during this time. Annual snowfall derived from the new bias-adjusted TD9813 precipitation data set exhibits a highly statistically significant increase until the late 1950s and a moderately significant decrease thereafter. Annual rainfall has declined significantly. Interpolations from the uneven, early station networks result in a biased depiction of spatially averaged precipitation, meaning that real local snowfall increases over the region were likely greater, and the rainfall decreases were possibly less, than the changes determined

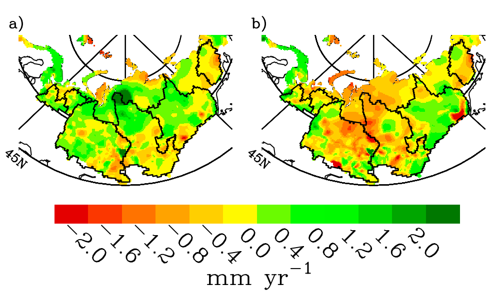

Figure 3. Trends (a) in derived snowfall and (b) in derived rainfall (1936–1999) from TD9813 *P* at each 25 × 25 km EASE-Grid cell encompassing the 6 largest Eurasian basins. Additional shaded areas are part of the larger pan-Arctic drainage basin of Eurasia. Spatially averaged values presented in this study (see Figures 1, 2, and 4) represent integrations across the 6 basins (west to east: *Severnaya Divina*, *Pechora*, *Ob*, *Yenisey*, *Lena*, *Kolyma*) outlined in bold.

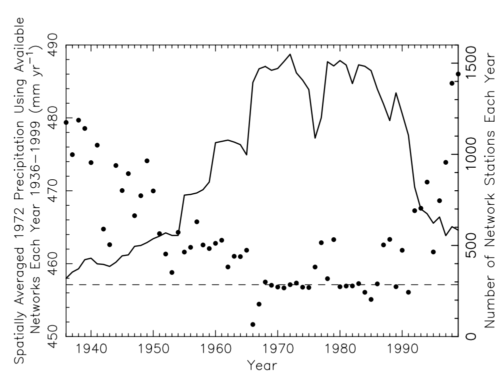

Figure 4. Annual total *P* for 1972 (dots) interpolated and spatially averaged from each yearly station network. The dashed line represents spatially averaged *P* for 1972, a year with the highest number of stations in the network between 1936–1999. The number of stations each year (solid line, right axis) mirrors the yearly network estimates of 1972 total precipitation.

from analysis of gridded data sets such as CRU and WM. While we believe that our partitioning of rainfall and snowfall contains no systematic bias, the method itself is crude, and we emphasize that the computed trends depend on the quality of interpolations from sparse precipitation and air temperature observations. Although our study suggests that increased cold season precipitation may be a significant driver of the discharge change, inherent biases in early meteorological networks and uncertainties in the historical precipitation observations render this finding intriguing, yet inconclusive.

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S. Frolking, R. B. Lammers, M. A. Rawlins, A. Shiklomanov, and C. J. Vörösmarty, Water Systems Analysis Group, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, 39 College Rd., Durham, NH 03824, USA. (michael.rawlins@unh.edu)

E. Linder, Department of Mathematics and Statistics, University of New Hampshire, Durham, NH 03824, USA.

C. J. Willmott, Center for Climatic Research, University of Delaware, Newark, DE 19716, USA.