Assessment of contemporary Arctic river runoff based on observational discharge records

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Assessment of contemporary Arctic river runoff based on observational discharge records

Richard B. Lammers, Alexander I. Shiklomanov, Charles J. Vörösmarty, Balázs M. Fekete, and Bruce J. Peterson

Abstract. We describe the contemporary hydrography of the pan-Arctic land area draining into the Arctic Ocean, northern Bering Sea, and Hudson Bay on the basis of observational records of river discharge and computed runoff. The Regional Arctic Hydrographic Network data set, R-ArcticNET, is presented, which is based on 3754 recording stations drawn from Russian, Canadian, European, and U.S. archives. R-ArcticNET represents the single largest data compendium of observed discharge in the Arctic. Approximately 73% of the nonglaciated area of the pan-Arctic is monitored by at least one river discharge gage giving a mean gage density of 168 gages per 10^6 km^2. Average annual runoff is 212 mm yr^-1 with approximately 60% of the river discharge occurring from April to July. Gridded runoff surfaces are generated for the gaged portion of the pan-Arctic region to investigate global change signals. Siberia and Alaska showed increases in winter runoff during the 1980s relative to the 1960s and 1970s during annual and seasonal periods. These changes are consistent with observations of change in the climatology of the region. Western Canada experienced decreased spring and summer runoff.

1. Introduction

The Arctic Ocean receives 11% of the world's river flow while containing only 1% of the global volume of seawater [Kalinin and Shiklomanov, 1974]. Twenty-five percent of the world's continental shelf area is found in the Arctic Ocean. Since the Arctic Ocean covers only about 14.2 million km^2 [Ivanov, 1976] and its drainage basin covers 19 million km^2 [Shiklomanov et al., 1999], it is the most river-influenced and landlocked of all oceans [Vörösmarty et al., 2000]. The influence is pronounced on the shallow shelf regions especially in Russia. The sensitivity of the Arctic region to global warming is predicted to be great and to span a wide array of Earth system processes. This sensitivity includes possible changes to the terrestrial biosphere with respect to vegetation [e.g., Foley et al., 1994], permafrost depth and dynamics [Nelson and Anisimov, 1993; Kane et al., 1990], carbon and nutrient biogeochemistry [Vörösmarty et al., 1997a], and feedbacks to the climate system [Budyko, 1990; IPCC, 1990, 1995, 1998; Boer et al., 1992]. Changes in the high-latitude terrestrial biosphere already have been documented through remote sensing [Myneni et al., 1997].

There are also concerns about how such progressive changes influence freshwater inputs to the Arctic coastal zone and their attendant effects on the formation of sea ice and of Atlantic deep water [Broecker, 1997; Rudroy and Baker, 1993]. River discharge into the Arctic Ocean in conjunction with the introduction of relatively low salinity Pacific waters entering through the Bering Sea fosters stratification that affects the formation of sea ice with corresponding feedbacks to the Arctic and global climate systems. Arctic drainage basin river flow is thus likely to serve an important role in regulating the heat balance of the planet [Kellogg, 1983; Mysak et al., 1990]. The freshwater cycle of the Arctic therefore takes on a central role in our understanding of the influence of global change on terrestrial ecosystems and on the connection of the Arctic landmass to the Arctic Ocean.

Despite the importance of the Arctic region's water cycle, a coherent picture of pan-Arctic discharge and runoff is lacking. The primary objective of this paper is to establish a well-documented contemporary baseline by which to judge future changes in observed runoff. A secondary objective is to analyze the spatial distribution of observed annual runoff and its seasonal components across the pan-Arctic drainage system and to document any trends in the station records over the last 30 years. The paper begins by describing the pan-Arctic database in terms of the spatial and temporal distribution of stations and observations. Next, we present the annual and seasonal characteristics of the runoff for the pan-Arctic region. The paper concludes with an assessment of changes in the runoff of the pan-Arctic drainage system over the 30 year time period. We analyze several characteristics of this database, including its spatial and temporal representativeness, its geography, the statistical nature of the observed hydrographs, and trends in runoff. This archive is available to the research community freely and without restriction (http://www.R-arcticnet.sr.unh.edu/).

2. Background on Arctic Hydrographic Information

We have defined the pan-Arctic region (Figure 1) to constitute all land area draining into the Arctic Ocean as well as those regions draining into the Hudson Bay, James Bay, Hudson Strait, and the Bering Strait. For completeness we include the large, permafrost-dominated drainage system of the Hudson Bay region [AMAP, 1998]. The Yukon and Anadyr Rivers draining into the
Figure 1. Pan-Arctic river system drainage organized by sea boundaries. (a) The sea basin boundaries are based on a digital river network at 30 min grid cell resolution (STN-30p). Shaded areas represent areas outside of the pan-Arctic drainage system. (b) The drainage network and gages for basins with areas greater than 10,000 km². The polar view of the Northern Hemisphere covers all areas north of 45°N.

northern Bering Sea supply a large amount of freshwater discharge to the Arctic Ocean via the north-flowing oceanic currents through the Bering Strait [AMAP, 1997], and for this reason we also include them in these data. We have partitioned the Arctic Ocean into 16 regional seas (Figure 1a) based on divisions given by AARI [1985] and Vorösmarty et al. [2000].

Most studies of Arctic discharge are specific to small field sites [e.g., Roulet and Woo, 1986; Slaughter et al., 1995; Hinzman et al., 1996] or restricted to local regions [Ivanov and Osipova, 1974; Plikin, 1978; Woo, 1984] and single basins, such as the Yenesei [Shiklomanov, 1994, 1995], the Mackenzie [Kite et al., 1994], or the Nelson-Churchill [Westmancott and Burn, 1997].

Arctic hydrography has also been analyzed in the context of global water balance. Baumgartner and Reichel [1975] and Korzoun et al. [1978] present maps and summary statistics on runoff regime and mean annual runoff. Both sets of maps are at a coarse scale and are dated. Baumgartner and Reichel maps are at a scale of 1:30 M with data ending at 1969, while the Korzoun et al. [1978] maps are 1:20 M with data ending at 1972. Because of the coarse scale, both show very general regional trends. Recently, Vorösmarty et al. [1996a] presented discharge records for approximately 1000 stations globally, of which 101 were in the Arctic Ocean watershed. Discharge data are also available through the World Meteorological Center Global Runoff Data Center [GRDC, 1996]. More recently, Shiklomanov et al. [1999] produced estimates of discharge from different regions within the pan-Arctic.

The first assessment of runoff variability for the Russian component of the Arctic drainage system was given by Zaikov [1946]. A detailed analysis of inflow variability into the Russian Arctic seas, based on observational data from the most downstream sites, was contributed by Antonov and Morozova [1957] and Antonov [1964] and later by Ivanov [1976, 1996], which included the entire Arctic basin. Voskresenski [1962] assessed the spatial distribution of long-term annual runoff for all of Russia on the basis of discharge measurements and water balance calculations for engaged areas. More detailed long-term runoff maps for the Russian Arctic drainage system were prepared at the Regional Roshydromet branches as a part of regional professional reports of the former Soviet Union surface water resources [Russian Hydro-meteorological Service, 1973]. Maps of long-term annual and monthly runoff for the Arctic drainage basin were also given by AARI [1985], based on data up to 1980.

Sanderson, 1969] using Thornthwaite potential evapotranspiration methods. Hare and Hay [1971] concluded that seasonal water balances could not be accurately calculated in northern Canada given the limited hydrometeorological record. However, they did produce their own maps of mean annual runoff from the gage record. Improved annual runoff surfaces were developed later [Fisheries and Environment Canada, 1978].

Although such studies provide important benchmarks by which to assess future change, they lack coherence in spatial scale and vary significantly in the time and space domain represented. For the most part, they are not digital in format and therefore cannot be easily employed in other research applications. We describe here a regional, digital data bank of observed discharge and runoff across the pan-Arctic region (Figure 1), R-ArcticNET version 2.0. The river discharge data base is composed of monthly data from 1877 to 1996. We focus on monthly time steps to facilitate the assembly and distribution of a long time series of discharge and runoff and to construct high quality climatologies. Observational data of the kind represented by R-ArcticNET should support a wide variety of Earth System studies including large-scale water balance and river flow modeling [Vörösmarty et al., 1998a, 1996b; Arnell, 1995; Oki et al., 1993; Roads et al., 1994], validation of global circulation models [Kite et al., 1994; Sausen et al., 1994; Liston et al., 1994] and estimating the effects of global change on water resources [Arnell et al., 1996; Shuklomanov, 1998; Miller and Russell, 1992].

3. R-ArcticNET Database

The database, R-ArcticNET v.2.0, described in this paper, comprises information from 3754 gaging stations for discharge data collected over the pan-Arctic. These data were used to characterize the spatial and temporal distribution of the pan-Arctic gages observational hydrographic record. A subset of this data set was used to generate gridded runoff fields. This subset contained 783 gages, the selection of which is described in section 3.3 below.

3.1. Data Sources and Characteristics

R-ArcticNET is a compendium of monthly mean discharge data drawn from original hydrometeorological archives (Table 1). Version 2.0 of the R-ArcticNET holds data from 3754 hydrological sites for the pan-Arctic drainage system. The data set represents a significant enhancement over currently available digital databases maintaining continental or global coverage. These include the RivDIS version 1.0 and 1.1 data sets based on UNESCO records [Vörösmarty et al., 1998b, 1996a] maintained within the UNH Global Hydrological Archive and Analysis System and at the Oak Ridge National Laboratory NASA Distributed Active Archive. R-ArcticNET also enriches the current global holdings [Grabs et al., 1996] and Arctic GEWEX/ACYSYS database [GRDC, 1996] maintained by the WMO Global Runoff Data Center in Koblenz, Germany. The Eurasian gages in R-ArcticNET include data from Russia and other former states of the Soviet Union, Norway,
Mongolia, Finland, and Iceland. Much of the data for Russia was digitized from original hydrological yearbooks. The data for Canada was obtained from the Canadian river discharge CD-ROM HYDAT [Environment Canada, 1994]. Alaskan discharge data were supplied by the USGS office in Anchorage, Alaska (D.F. Meyer, personal communication, 1997) and over the Internet from the Hydro-Climatic Data Network for the Souris-Red-Rainy region [Slack et al., 1993]. Nonetheless, variations between different agencies tend to use vertical-axis current meters sampled at fewer points in the vertical [Pelletier, 1990]. Typical errors for measured discharge are in the range of ±2–5% for nonice conditions in river cross sections without flood plains and ±5–12% for rivers with flood plains [Rantz et al., 1982; Russian Hydrometeorological Service, 1970]. Maximum errors are found in mountain rivers and can be as high as 25%. Errors for calculated monthly discharge tend to be the same or slightly higher as the measured discharge. When temperatures are low, the discharge estimates are much less certain due to anchor ice, frazil ice, and backwater conditions. Wedel [1990] reports ±10% for conditions under rough ice, while the Russian Hydrometeorological Service [1970] reports that errors for river discharge measurements under ice conditions do not change appreciably from ice-free conditions.

### 3.2. Spatial Distribution of the Gages

The boundaries of the pan-Arctic drainage basin were defined using a digital river network, STN-30p, given by Vörösmarty et al. [2000], organized at a 30 min × 30 min (longitude × latitude) grid spacing (Figure 1b). The digital river network excludes the 1,802,000 km² Greenland ice cap [Gleick, 1993] but does include the non-ice-covered portions of Greenland. Within the confines of the pan-Arctic drainage basin at this resolution there are 1967 individual drainage systems discharging to the ocean and encompassing an area of approximately 22.4×10⁶ km², not including permanently ice-covered regions.

Table 1 compares the efficacy of the two river data sets. The RivDis v. 1.0 data were developed using the Hydro-Climatic Data Network and the R-ArcticNet data were developed using the Global Runoff Data Center [WMO-GRDC, 1996]. The RivDis v. 1.0 data set contains 2233 gauges, whereas the R-ArcticNet data set contains 1521 gauges. The RivDis v. 1.0 data set includes gauges in North America, Europe, and Asia, whereas the R-ArcticNet data set includes gauges in North America, Europe, Asia, and Africa. The RivDis v. 1.0 data set includes gauges in North America, Europe, Asia, and Africa, whereas the R-ArcticNet data set includes gauges in North America, Europe, Asia, and Africa.

### 3.3. Temporal Distribution of the Gages

R-ArcticNet represents a long-term time series of monthly river data with holdings extending from prior to 1900 (for four Canadian and five Russian gages) until the early 1990s. The length of record for individual gages is extremely variable. Figure 4...
Table 2. Distribution of Drainage Area, River Discharge Gages, Gaged Drainage Area, and Gage Density in the Pan-Arctic Region for All Nonglaciated Areas

<table>
<thead>
<tr>
<th>Sea Basin</th>
<th>Drainage Area ($10^5$ km$^2$)</th>
<th>Number of Gages</th>
<th>Gaged Area (% Drainage Area)</th>
<th>Gage Density (Gages/10^6 km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Archipelago</td>
<td>1231</td>
<td>23</td>
<td>17</td>
<td>18.7</td>
</tr>
<tr>
<td>Arctic sub-ocean</td>
<td>73</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Baffin Bay</td>
<td>164</td>
<td>1</td>
<td>0</td>
<td>6.1</td>
</tr>
<tr>
<td>Barents Sea</td>
<td>1279</td>
<td>326</td>
<td>77</td>
<td>254.9</td>
</tr>
<tr>
<td>Beaufort Sea</td>
<td>2090</td>
<td>477</td>
<td>89</td>
<td>228.2</td>
</tr>
<tr>
<td>Bering Strait</td>
<td>1218</td>
<td>102</td>
<td>83</td>
<td>83.7</td>
</tr>
<tr>
<td>Chukchi Sea</td>
<td>234</td>
<td>4</td>
<td>24</td>
<td>17.1</td>
</tr>
<tr>
<td>East Siberian Sea</td>
<td>1345</td>
<td>85</td>
<td>70</td>
<td>63.2</td>
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<td>Foae Basin</td>
<td>272</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Greenland Sea</td>
<td>99</td>
<td>2</td>
<td>13</td>
<td>20.2</td>
</tr>
<tr>
<td>Hudson Bay*</td>
<td>3308</td>
<td>1605</td>
<td>79</td>
<td>485.2</td>
</tr>
<tr>
<td>Hudson Strait</td>
<td>468</td>
<td>30</td>
<td>61</td>
<td>64.1</td>
</tr>
<tr>
<td>Kara Sea*</td>
<td>6615</td>
<td>898</td>
<td>78</td>
<td>135.4</td>
</tr>
<tr>
<td>Laptev Sea</td>
<td>3632</td>
<td>188</td>
<td>89</td>
<td>51.8</td>
</tr>
<tr>
<td>Norwegian Sea</td>
<td>160</td>
<td>6</td>
<td>5</td>
<td>37.5</td>
</tr>
<tr>
<td>South Greenland</td>
<td>216</td>
<td>7</td>
<td>5</td>
<td>32.4</td>
</tr>
<tr>
<td>North America</td>
<td>8956</td>
<td>2233</td>
<td>65</td>
<td>249.3</td>
</tr>
<tr>
<td>Europe</td>
<td>13448</td>
<td>1521</td>
<td>78</td>
<td>113.1</td>
</tr>
<tr>
<td>Greenland Ice Cap</td>
<td>1802</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>24206</td>
<td>3754</td>
<td>68</td>
<td>155.1</td>
</tr>
</tbody>
</table>

*Includes internal drainage in the Nelson River.

*Includes internal drainage in the Ob River.

shows the distribution of gages by length of record. For shorter time periods, less than 20 years, there are many more North American gages than those in Eurasia. For long record lengths, greater than 40 years, Eurasian gages are more frequent. Figure 5a shows the total number of gages containing at least one monthly data point in any given year for Eurasia, North America, and the entire pan-Arctic. Early in the twentieth century the number of gages in North America increased sharply from near zero to about 200 stations. This coincided with the rapid increase in population in western Canada. This level declined gradually until the 1940s which saw an increasing number of monitoring stations until a peak was reached in the mid-1980s. This is followed by a small decline as some gages in North America were shut down [Wahl et al., 1995]. The gages in Eurasia, predominantly Russia, show a sudden increase during the mid-1930s corresponding to increasing population and industrialization in Siberia resulting from policies instituted during the Stalin era. The number of gages increased steadily until 1985 at an average rate of about 25 new stations per year. After 1985 the number of Eurasian monitoring stations within the data base declines dramatically. In Russia there are two

Figure 2. Distribution of gages per latitude zone. This figure illustrates the predominance of the lower latitudes in the pan-Arctic discharge record. The latitude for gages with drainage areas less than 10,000 km$^2$ is given by the gage location. The latitude for gages with drainage areas greater than 10,000 km$^2$ is given by the centroid (center of mass) of the subbasin upstream from the gage. There are 3482 gages shown.
reasons for the large recent decline in the number of gages available in the database. On the basis of information from the Network Department of the State Hydrological Institute, St. Petersburg, Russia, (I. Shiklomanov, personal communication, 1998) up to 30% of the gages in the Russian Hydrometeorological Service have been closed. Additionally, the apparent lack of river gage entries also results from delays in publishing the hydrological yearbooks. These yearbooks are the official source of hydrological information for Russia and it is these books which were used to digitize the Russian data in R-ArcticNET. For the pan-Arctic as a whole, the maximum number of gages appear between 1970 and 1985 with more than 2000 stations reporting discharge. After 1985 the total number of gages in the database decreases dramatically.

In terms of land area monitored relative to the total land area of the pan-Arctic region it can be seen that over 70% of the Eurasian pan-Arctic landmass has been monitored by at least one gage since 1936 (Figure 5b). In North America, total gaged land did not surpass 50% until 1964. It is also important to note that the large decrease in Eurasian gages after 1985 does not significantly reduce the total monitored area since the gages which closed, or do not

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**Figure 3.** Number of gages in the database per total land area drained. The frequency of gages per drainage area class (log scale) is divided into those for both North America and Eurasia. The largest number of gaged drainage basins are on the order of 1000 km$^2$. There are 3487 gages where drainage area is known.

**Figure 4.** Number of gages by years of record for Eurasia, North America, and the entire pan-Arctic. The length of record represents only those years containing at least one monthly data point to avoid overcounting years for gages with multiyear gaps. Solid, pan-Arctic; dotted, North America; and dashed, Eurasia.
North American records show missing monthly data to account for nonreporting stations during the months December through March. In the southern portion of the North American Arctic, the very large numbers of missing data relative to Eurasia are primarily due to gages in the Prairie Provinces of Canada with irregular observational periods. There are 95 gages from Canada (and two from Eurasia) which have 1 year or less of data. These gages represent samplings of local runoff generation and have been kept in the database.

### 3.4. Estimates of Runoff

To characterize the large-scale spatial features of runoff across the pan-Arctic basin, a subset of gages having large drainage areas was created. The data subset was defined on the basis of gage attribute information, including the time period covered. All gages with data falling within the time period from January 1960 to December 1989 were selected. This corresponds to the maximum number of gages covering the pan-Arctic (Figure 5a). Additionally, only those gages with a drainage area of 10,000 km² or more were chosen. This drainage area threshold is the minimum size that can be expected to resolve drainage basins when using our 30 min STN-30p digital river network for drainage basin delineation [Vörösmarty et al., 2000] or runoff mapping [Fekete et al., 1999]. There were 813 sites that fulfilled the above criteria. Using STN-30p, Digital Chart of the World [ESRI, 1993] and the 1:1×10⁶ scale ONC maps [DMAAC, 1980-1986], the gage topology was constructed for the full subset of gages. After closer inspection an additional 30 gages were removed from the subset due to incorrect coordinates or large anomalies in the discharge values, which we believe result from either errors in data entry and/or unit conversion or significant anthropogenic disturbance (i.e., water engineering works). The final grouping of discharge gages used for generating runoff surfaces for the pan-Arctic region numbered 783. We call this subset R-ArcticNET v.2.0sub.

Calculations of runoff were made for all areas between the river discharge gages referred to as “interstation” areas (Figure 6) following a methodology presented by Arnell [1995] and Fekete et al. [1999]. Monthly runoff values for all interstation areas were calculated by subtracting all upstream discharge values from the monthly discharge time series associated with the representative downstream gage. Runoff was then calculated by dividing the interstation discharge by the interstation drainage area. The

![Figure 5](image-url)
4. Results and Discussion

Runoff fields at 30' spatial resolution (Plate 1) were used to generate 30 year mean runoff statistics on annual and seasonal time steps for North America, Eurasia, and the entire pan-Arctic as well as for individual seas (Table 3). Annually averaged runoff ranges from a low of 164 mm in the Arctic archipelago to 511 mm in the Chukchi Sea basin. The average for the pan-Arctic is 212 mm yr\(^{-1}\). As expected for this region, all sea basins show very low winter runoff, and in all cases the highest values occur during spring runoff. Spring runoff tends to range between 46% and 66% of annual runoff, with the Hudson Bay basin having runoff more evenly distributed throughout the year and the Laptev, Kara, and East Siberian Sea basins having the largest seasonality due to the strong continental climate of Siberia. Also included in Table 3 are the mean number of gages represented in each of the spatial regions. There are several sea basins that have fewer than 20 gages on average for any given monthly time step. These are the Arctic archipelago, Chukchi Sea, and Hudson Strait, and therefore any results relating to these basins will be more sensitive to temporal changes in the representative gages. More robust estimates, due to the large number of gages, are expected for the Kara Sea and Hudson Bay basins.

The long-term annual runoff field is shown in Plate 1. High runoff can be seen in areas of (1) orographic influence; the mountainous southern regions of central and eastern Siberia and along the Rocky Mountains in western Canada, and (2) those regions receiving precipitation from cyclonic activity; the European part of Russia and eastern Hudson Bay drainage in Quebec. Low-runoff regions are seen in the southwestern Ob' basin, the Selenga basin in northern Mongolia, and the western Canadian Arctic drainage of the Nelson River system. These basins tend to be dry due to their position on the lee side of mountain ranges and their continental climates. The large-scale structure of the runoff surface is consistent with the long-term runoff maps given by AARI [1985] and by Fisheries and Environment Canada [1978]. Another comparison that can be made is to surfaces of precipitation minus evaporation (P-E fields) generated from climate models or calculated from rawinsonde measurements. The fine-scale features of the runoff surfaces do not, however, correspond to existing P-E fields [Serreze et al., 1995; D. Bromwich, personal communication, 1999]. This is a result of poor station densities of rawinsonde archives [Serreze et al., 1995] and the coarse underlying scales of reanalysis products [Kalnay et al., 1996] which inhibit resolving the fine-scale spatial features of the runoff fields (approximately 100-200 km in extent) such as those in southern Siberia.

Time series for the entire gaged pan-Arctic basin as well as five of the sea basins from Table 3 are shown in Figure 7. The Mann-Kendall nonparametric test for trend [Helsel and Hirsch, 1992] was used to check the annual and seasonal time series. Statistically significant increases were found only in the winter months in the Beaufort, Kara, Laptev, and Bering Sea drainage regions as well as for the entire pan-Arctic during the winter. However, these time series tend to mask regional differences. To better understand the spatial differences that exist in the runoff time series, the 30 year period was separated into the first 20 years (1960-1979) and the last 10 years (1980-1989). The asymmetric temporal division was chosen to illustrate the possible effects of Arctic climatic variability resulting from higher annual and seasonal temperature effects are minor as yet for the pan-Arctic region as a whole compared to other parts of the world [Shiklomanov et al., 1999; Dynesius and Nilsson, 1994; Vörösmarty et al., 1997b].
Plate 1. Long-term annual runoff surfaces for the pan-Arctic region for the period January 1960 to December 1989. White areas within the southern Ob’ basin represent internal drainage basins without monthly data points throughout the year. Note the large regions along the coast of the Arctic Ocean which have no runoff values (unshaded) as they are ungaged. The majority of the basin, 73%, has been monitored routinely from 1960 to 1990.
Deviation in Mean Annual and Seasonal Runoff

(a) Annual  (b) Winter

(c) Spring  (d) Summer/Fall

Plate 2. Deviation in mean annual and seasonal runoff. Deviation maps for annual, winter, spring, and summer/fall showing the percentage difference between the long-term annual runoff surfaces for the time periods 1960-1979 versus 1980-1989. Differences greater than ± 10% are highlighted with yellow, indicating a decrease in runoff; and blue, indicating an increase in runoff during the 1980s relative to the 1960-1979 time period. Seasons are defined as in Figure 7.
Table 3. Annual and Seasonal Long-Term Runoff by Sea Basin (mm/time period)

<table>
<thead>
<tr>
<th>Selected Sea Basins</th>
<th>Annual (mm yr⁻¹)</th>
<th>Winter (mm season⁻¹)</th>
<th>Spring (mm season⁻¹)</th>
<th>Summer/Fall (mm season⁻¹)</th>
<th>Mean Gages per Time Step²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Archipelago</td>
<td>164</td>
<td>8</td>
<td>93</td>
<td>65</td>
<td>3.6</td>
</tr>
<tr>
<td>Barents Sea</td>
<td>349</td>
<td>35</td>
<td>225</td>
<td>89</td>
<td>45.6</td>
</tr>
<tr>
<td>Beaufort Sea</td>
<td>200</td>
<td>26</td>
<td>108</td>
<td>66</td>
<td>44.5</td>
</tr>
<tr>
<td>Bering Strait</td>
<td>256</td>
<td>16</td>
<td>148</td>
<td>92</td>
<td>20.9</td>
</tr>
<tr>
<td>Chukchi Sea</td>
<td>511</td>
<td>24</td>
<td>280</td>
<td>212</td>
<td>0.9</td>
</tr>
<tr>
<td>East Siberian Sea</td>
<td>181</td>
<td>1</td>
<td>115</td>
<td>64</td>
<td>12.1</td>
</tr>
<tr>
<td>Hudson Bay</td>
<td>192</td>
<td>34</td>
<td>89</td>
<td>69</td>
<td>97.7</td>
</tr>
<tr>
<td>Hudson Strait</td>
<td>508</td>
<td>39</td>
<td>286</td>
<td>182</td>
<td>6.8</td>
</tr>
<tr>
<td>Kara Sea</td>
<td>186</td>
<td>16</td>
<td>119</td>
<td>50</td>
<td>168.4</td>
</tr>
<tr>
<td>Laptev</td>
<td>210</td>
<td>7</td>
<td>139</td>
<td>63</td>
<td>51.6</td>
</tr>
<tr>
<td>North America b</td>
<td>219</td>
<td>28</td>
<td>114</td>
<td>77</td>
<td>34.7</td>
</tr>
<tr>
<td>Eurasia b</td>
<td>208</td>
<td>14</td>
<td>134</td>
<td>59</td>
<td>55.7</td>
</tr>
<tr>
<td>Pan-Arctic d</td>
<td>212</td>
<td>19</td>
<td>127</td>
<td>65</td>
<td>45.2</td>
</tr>
</tbody>
</table>

For land area with drainage areas larger than 10,000 km² and at least one monthly data report within the time period January 1960 to December 1989.

*Annual values represent the calendar year from January to December; winter is December, January, February, March; spring is April, May, June, July; summer/fall is August, September, October, and November.

1For this table the Bering Strait is considered North American and the Chukchi Sea is considered Eurasian.

2Column 6 represents the mean number of gages contributing to all years (1960-1989) for annual and seasonal runoff surfaces.

The outflow of meltwater and ice calving from the Greenland ice sheet, not included in this table, is estimated to be approximately 237 km³ yr⁻¹ (132 mm yr⁻¹) and 316 km³ yr⁻¹ (175 mm yr⁻¹), respectively (C. E. Baggild, personal communication, Geological Survey of Denmark and Greenland, 1999). Runoff estimates calculated using Greenland Ice Cap area from Table 2.

For land area with drainage areas larger than 10,000 km² and at least one monthly data report within the time period January 1960 to December 1989.

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Figures for northern latitudes after 1980 and larger values of the North Atlantic Oscillation Index after 1980 [Hurrell, 1995]. Long-term average annual and seasonal runoff surfaces were created and the percentage change between the two periods was calculated (Plate 2). The annual, spring, and summer/fall maps show a consistent pattern. River runoff declined in much of the Ob basin and western Canada. Between 1960-1979 and 1980-1989 there was increased runoff in the eastern Northwest Territories of Canada and the mountains dividing the Yenesey and Lena basins. The winter presents a different picture in which there is

![Figure 7. Annual, winter, spring, and summer/fall runoff for sea drainage areas covering five sea basins and the entire monitored pan-Arctic. Winter represents December, January, February, and March. Spring is April, May, June, and July. Summer/fall is August, September, October, and November. Solid, annual; short dashed, winter; long dashed, spring; and dotted, summer-fall.](image-url)
much greater spatial variability throughout Canada and increased runoff in Alaska and the Yukon and in large parts of Siberia and in the European part of Russia.

The increasing runoff values during the 1980s are consistent with observed patterns of increasing Northern Hemisphere temperatures related to observed changes in atmospheric circulation patterns [Rogers and Mosley-Thompson, 1995; Trenberth and Hurrell, 1994; Hurrell, 1995, 1996]. Serreze et al. [2000] show evidence of recent climate change in the northern high latitudes using observational evidence from atmospheric, cryospheric, oceanic, and terrestrial sources. The decade of the 1980s, for example, has seen an increase in land surface temperatures in the northern latitudes with the greatest changes occurring during the winter months [Skinner and Gullett, 1993; Graça et al., 1999]. These temperature changes are linked to changes in the atmospheric circulation patterns over the oceans through the North Pacific (NP) index [Trenberth and Hurrell, 1994] and North Atlantic Oscillation (NAO) index [Hurrell, 1995]. A low NP index is linked to an eastward shift in the Aleutian low during the winter which causes increased temperatures over northwest North America [Trenberth and Hurrell, 1994; Hurrell, 1996]. A high NAO index shows deepening in the Icelandic low in winter with increased westerlies reducing surface temperatures in Labrador and west Greenland and increasing temperatures in northern Europe and Russia [Hurrell, 1995, 1996; Rogers and Mosley-Thompson, 1995]. Increasing winter temperatures have the effect of reducing snow cover as observed by Brown and Goodison [1996] and increasing rain to snow ratios [Mekis and Hogg, 1999] which result in increases to winter runoff. Additionally, some of the spring snowmelt will be shifted into the wintertime period where river flows tend to be much lower and therefore more sensitive to changes. This has been observed for the Yenisey basin by Shiklomanov [1994] and for the Churchill and Nelson basins by Westmacott and Burn [1997].

The reasons for reduced runoff throughout western Canada and parts of the Ob' basin during the rest of the year is less clear. Some of the change will be a result of the snowmelt shifting to the winter as discussed above; however, these amounts tend to be small relative to the overall spring runoff, and the regions of lower runoff are not coincident with the increased winter runoff. Some of the reduced runoff can also be linked to anthropogenic changes. Some basins in western Canada have some impoundment of rivers. However, the region of observed reduced runoff extends north of the Canadian prairies, beyond those areas of significant impoundments. The primary remaining source of reduced river discharge is reduced precipitation. However, increases have been found in observed precipitation for these regions of Canada for annual [Groseman and Easterling, 1994] and seasonal [Mekis and Hogg, 1999] time periods, although these studies use longer time periods covering 50 to 100 year periods which are not directly comparable to the 30 year period in this study. Additionally, precipitation data are well known to contain large errors which tend to be downward biased especially in winter [Groseman and Easterling, 1994]. As a result, more work is needed to better close the water budget for these regions and to interpret these spatially and temporally complex changes.

5. Conclusions

A river discharge database, containing 3754 gages, was assembled which represents the pan-Arctic region of North America and Eurasia. The spatial distribution of the data showed that south of 56oN the gaged record tended to have excellent coverage, while sparse gage densities occurred north of 69oN. The majority of gages had drainage areas in the range 102 to 104 km2. The temporal distribution of the data demonstrated that large numbers of gages were opened in the second half of the twentieth century with greater than 1500 gages covering the pan-Arctic region after 1960. A noticeable reduction in gage numbers has occurred after 1985 due to delays in publishing the data and the abandonment of discharge gages. This is a major concern for the Arctic where strong evidence points to large changes in the regional climate [Serreze et al., 2000]. The capacity to monitor hydrologic change in this region has been seriously reduced during the period when the scientific community is searching for indications of global change and must determine the magnitude and distribution of these changes.

The R-ArcticNet v2.0 database was used to establish a near-contemporary benchmark for runoff against which the paleo, historical, and future states of Arctic land surface hydrology can be compared. A subset of the database was used to generate gridded runoff surfaces covering the gaged portion of the pan-Arctic, 68% of the entire pan-Arctic landmass. A long-term annual runoff field (Plate 1) highlighted regional differences in river discharge. The database shows an Arctic region with large differences in surface water availability. Runoff values greater than 400 mm yr{-1} were found in Quebec, the Rocky Mountains, the Urals and southern Siberia, while very low runoff, less than 40 mm yr{-1}, was observed in the southern Ob' and western Canada basins. The gridded surfaces were aggregated into regions which drain into 16 Arctic sea basins. Annual and seasonal river runoff time series for 1960-1989 showed significant trends during the winter months by drainage into these sea basins as well as the Arctic as a whole (Figure 7). These changes are probably due to increases in temperature shifting more of the snowmelt signal into the winter. These changes were clearly seen in the changes in winter runoff between the 1960-1979 and the 1980-1989 time periods (Plate 2). Other regional patterns were highlighted in the annual, spring, and summer/fall deviation maps. Large parts of the Canadian west and Ob' River basins had decreased river runoff for other seasons during the 1980s. While the spring and summer/fall runoff did not show any significant trends over the river basins, their spatial coherence does suggest an important effect warranting further investigation into the major water balance variables of precipitation and evapotranspiration.

The R-ArcticNet data compendium, based on archives from several hydrometeorological services, represents the single largest collection of observed hydrographic information for the Arctic. It supplements additional holdings for other regions and other types of hydrometeorological data of the Global Hydrological Archive and Analysis System (GHAAAS) at the Institute for the Study of Earth Oceans and Space at the University of New Hampshire. The discharge data are spatially and temporally harmonized, which allows for improved analysis of river discharge, regional runoff patterns throughout the entire pan-Arctic, and total freshwater flux to the ocean. Gridded runoff fields at 30 min spatial resolution allow the discharge data to be aggregated over a variety of spatial domains such as river basins, drainage by sea basin, or continents. Climatological runoff by drainage into sea basins is an example used in this paper.

R-ArcticNet will be of use to a broad cross section of Earth System scientists, including those interested in continental-scale hydrological budgets, terrestrial net primary production, atmospheric climate modeling, and ocean modeling, which all require a quantification of runoff from the terrestrial landscape to the Arctic Ocean. It provides a geographic description of discharge and...
runoff and provides important model calibration and validation targets. R-ArcticNet version 2.0 is now available over the WWW through the Institute for the Study of Earth, Oceans, and Space, University of New Hampshire at http://www.R-ArcticNet.unh.edu/ and on CD-ROM through the National Snow and Ice Data Center, Boulder, Colorado.


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