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Observational Evidence of Increases in Freshwater Inflow to the Arctic Ocean

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Abstract

Analysis of mass balance data from arctic mountain and subpolar glaciers with an aggregate area of more than $300*10^3$ km^2 reveals that these glaciers were the main source of increased freshwater inflow to the Arctic Ocean over the 1961–1998 period. The sum of net water inflow from glaciers was larger than net water inflow from rivers in the panarctic region, and the combined contribution from both glacier and land components had accelerated. Compared to the 1961–1990 averaged values, the largest combined contribution was observed at the end of the 1970s, declined in the 1980s, and began increasing again in the mid-1990s. Net glacier inflow supposedly increased due to Northern Hemisphere temperature warming. We attribute the increase in net river inflow to an increase in annual precipitation over the 50–70°N latitude belt in North America and Eurasia.

Introduction

The reported rapid freshening of the deep layers of the North Atlantic Ocean accompanied by a decrease in water salinity and predicted changes in global thermohaline circulation (Dickson et al., 2002) inspires further simulations of freshwater climate change–related studies (Peterson et al., 2002). Recent studies suggest that arctic river discharge is the main source of freshwater inflow to the Arctic Ocean (Vörösmarty et al., 2001; Shiklomanov et al., 2002; and Peterson et al., 2002). One study claims that arctic river discharge is a useful indicator of climate change in the panarctic region "because it provides an integrative measure of the continental water balance" (Peterson et al., 2002). In fact, the average annual rate of water discharge from 6 major Eurasian rivers increased at about 2.0 ± 0.7 km^3 yr^{-1} from 1936 to 1999 and is greater now (about 128 km^{3}yr^{-1}) than it was in the 1930s (Peterson et al., 2002).

Our study shows that discharge data measured from large river basins in the panarctic, may not "provide an integrative measure" of freshwater inflow to the Arctic Ocean because these data include only a small fraction of net glacier inflow to the ocean. The main glacier area in the arctic region has never been gauged. We demonstrate that the glacier net inflow to the Arctic Ocean, specifically the net glacier volume loss, has been comparable to the combined river net inflow from the largest panarctic rivers.

Panarctic Region and Main Components of Freshwater Inflow

For the purpose of this study, we define the panarctic region as the region north of the Arctic Circle. In addition, we include the area of river basins that contribute water to the Arctic Ocean, including glacier regions inside these basins. The entire area is about $31*10^6$ km^2. This includes Arctic Ocean 9×10^6 km^2 (Gleick, 1993). We calculated river discharge data from the R-ArcticNET Hydrographic Data Network during 1961–1993 (Lammers and Shiklomanov, 2001) and 1994–1998 (Shiklomanov, personal communication). We summarized data on annual river discharges for 9 major river basins in the panarctic (Lammers and Shiklomanov, 2001). We excluded the West European drainage basin from our calculations for a reason described later.

The panarctic region contains nearly 50% of the world's mountain and subpolar glacier area (Jania and Hagen, 1996). The majority of glaciers are in the Canadian, European, and Russian arctic islands and in several mountain regions (Table 1). Throughout the 20th century, arctic glaciers showed a negative mass balance; their volume has been decreasing in response to climate warming (Jania and Hagen, 1996; Dowdeswell et al., 1997; Serreze et al., 2000; Dyurgerov and Meier, 1997, 2000; Meier et al., 2003; Hinzman et al., 2004). Consequently, their net contribution to the Arctic Ocean is increasing.

We analyzed the recently updated observational results of freshwater inflow to the Arctic Ocean from mountain and subpolar glaciers in the panarctic, outside the Greenland ice sheet. The study area includes an aggregate glacier area of approximately $2.01*10^6$ km^2, divided between mountain and subpolar glaciers ($\sim0.343*10^6$ km^2) and the Greenland Ice Sheet ($\sim1.68*10^6$ km^2) (Dyurgerov, 2002; Church et al., 2001).

For our analysis we used the 1961–1998 period covered by the internationally coordinated glacier-monitoring program (Haeberli et al., 1998). Observational results of glacier volume change from this period were recently updated and are now available for the scientific community (http://instaar.colorado.edu/other/occ_papers.html).

The panarctic is divided into 10 large river basins (Fig. 1) that together cover the majority of the land area but, as stated above, do not include 92% of the glacier area (Greenland Ice Sheet not included). In order to further reduce in our calculations the amount of glacier discharge from all other freshwater sources integrated by rivers, we eliminated the West European basin from calculations of river inflow (Lammers and Shiklomanov, 2001), an area that includes the relatively large glacier areas of Iceland ($\sim$11,260 km^2) and Scandinavia ($\sim$2940 km^2). By doing this, we decreased the amount of overlap to 4%. Most of the remaining glaciers are in the Yukon River basin (about 10,500 km^2; Table 1), and contribute water to the Arctic Ocean through the Bering Strait. We failed to eliminate glacier runoff from discharged river runoff data in mountain ranges around the large Siberian rivers. This glacier area is small, less than 0.8% (Table 1). Therefore, 96% of glacier area in the panarctic is not included in the river runoff data and can be considered as direct meltwater inflow to the ocean. This allows us to calculate contributions of net river (nonglacier) and net glacier-melt inflows to the Arctic Ocean separately.

Freshwater Inflow to the Arctic Ocean

GENERAL CONSIDERATIONS

The size and importance of freshwater flux to the Arctic Ocean make the ocean very sensitive to changes in freshwater contribution.

TABLE 1

Surface area of glaciers in panarctic drainage basin outside the Greenland Ice Sheet

Region	Latitude/Longitude	Basin, ni, g/ng*	Area, km^2
Scandinavia		Atlantic and Baltic Sea, ni	2941.7
Iceland		Atlantic, ni	11,260
Khibiny Mts.	68.0 N, 34.0 E	ng	0.1
Chukotka Plateau and Pekul'ney		g	17.07
Taigonos Peninsula, Far East		g	2
Polar Ural		g	28.7
Byrranga Mts.	75.8 N, 107.8 E	g	30.5
Putorana Plateau	70.0 N, 92.0 E	g	2.54
Orulgan Range	68.1 N, 128.0 E	g	18.38
Kharaulakh Range		g	3
Cherskogo Range	65.0 N, 148.0 E	Indigirka, g	155.3
Koryak Range	62.0 N, 172.0 E	Anadyr', Bering Sea, ni	291.7
Suntar-Khayata Range		Indigirka, g	201.6
Kodar Range	57.0 N, 117.3 E	Lena, g	18.8
Sayany	52.5 N, 97.3 E	Enisey, g	34.1
Altay (Russian & Mongolian parts)	47.2 N, 90.5 E	Ob, g	1750
Kuznetskiy Alatau		g	6.8
Khrebet Saur	47.1.0 N, 85.3 E	Enisey, g	16.6
Baykal and Barguzin Ranges		g	6.2
East Arctic Islands			
Victoria	About 79.6.0 N, 35.0 E	ng	10.7
Franz Josef Land	81.0 N, 57.0 E	ng	13,735
Novaya Zemlya	75.0 N, 57.0 E	ng	23,645
Severnaya Zemlya	80.0 N, 97.0 E	ng	18,325.5
Ushakova Island	81.0 N, 80.0 E	ng	325.4
De Longa Island	77.0 N, 152.0 E	ng	80.6
Wrangel Island	71.5 N, 179.0 E	ng	3.5
Total			**56,100**
West Arctic Islands			
Svalbard	79.25−77.5 N, 13.33′−18.0 W	ng	36,611.70
Jan Mayen	71.1 N, 8.2 W	ng	116
Total		ng	**36,700**
Canadian Arctic Archipelago			
Ellesmere		ng	80,000
Ellesmere Ice Shelf		ng	500
Axel Heiberg	76.7–81.0 N, 87.4–94.7 W	ng	11,700
Devon		ng	16,200
Bylot		ng	5000
Baffin		ng	37,000
Coburg		ng	225
Meighen		ng	85
Melville		ng	160
North Kent		ng	152
others		ng	736
Total		ng	**151,800**
Greenland: small glaciers		ng	**70,000**
Total in Arctic Islands			**315,000**
Alaska			84
Brooks Range		Colville, ng	722.4
Yukon basin, including Wrangel, Kenai, Chugach, Alaska, Talkeetna, and Aleutian Ranges		g	10 500
Seward Penins. and Kilbuk Mtns		ng	233
Total			**11,455**
Total glacier area in panarctic, km^2	**entire area 328,556	gauged area 12,792	nongauged area 315,764

g, ng* = gauged/nongauged, ni = not included in our calculation; ** 14,493 km^2 of glaciers belongs to the West European basin and has not been included in the sum.

It is a small ocean, only about 2.5% of the world's ocean area ($361.1*10^6$ km^2). However, the Arctic Ocean receives more freshwater per unit area (307 mm yr^{-1}) than any other ocean on Earth (Baumgartner and Raichel, 1975).

The standard water balance of the terrestrial part of the region is:

$$R = P - E \pm \Delta \quad (1)$$

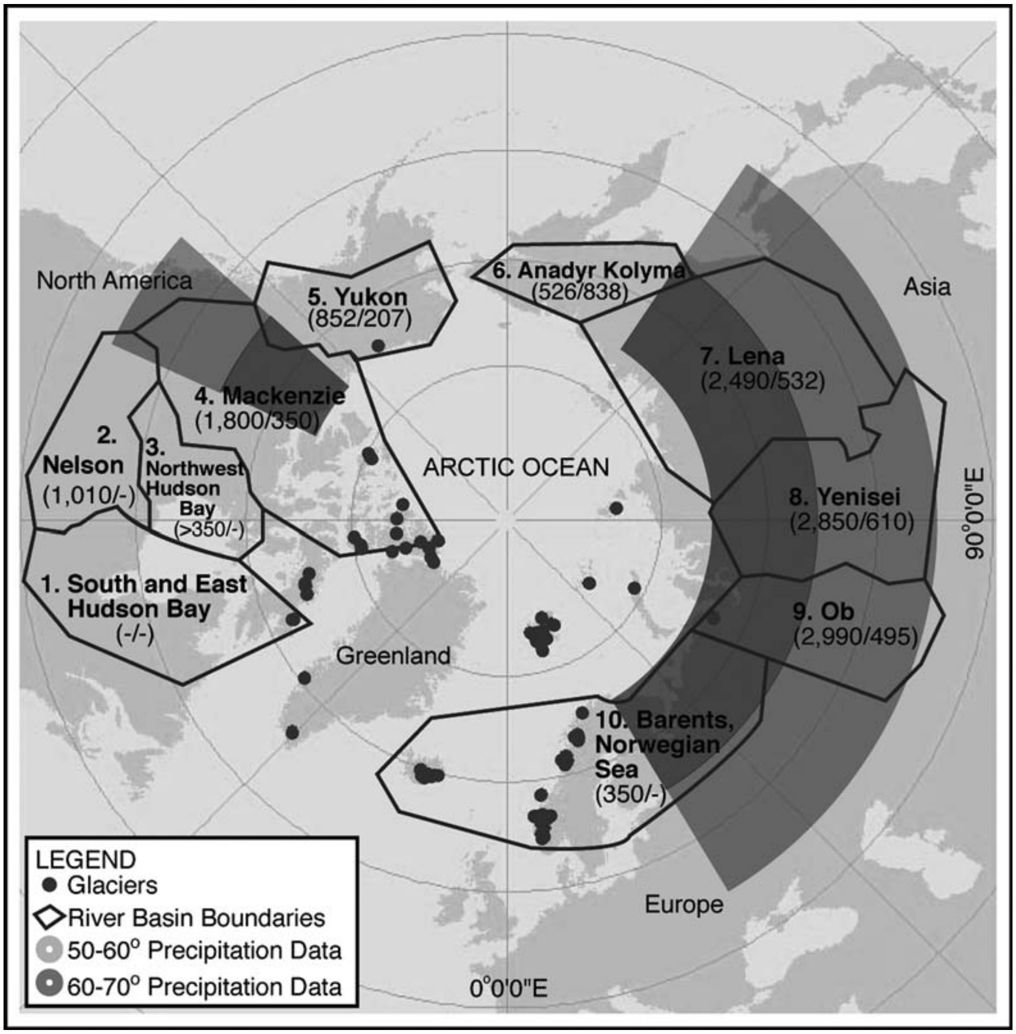

FIGURE 1. Map of panarctic river basins (basins are numbered from 1 to 10), benchmark glaciers, and precipitation data zones. Numbers in parentheses indicate basin area in 1000 km^2 and discharge in km^3/year, respectively (Lammers and Shiklomanov, 2002; Hulme, 1999).

where P is the rate of precipitation, E is the rate of evapotranspiration, R is the rate of surplus water (runoff and/or recharge), and Δ is the residual; all are in millimeters per year. The residual $\Delta = \pm W \pm F \pm b \pm U \pm \delta$ includes $\pm W$ – change in soil moisture content, $\pm F$ – change in permafrost moisture content, $\pm b$ – change in ice storage on land surface (or glacier mass balance), $\pm U$ – change in water usage, $\pm\delta$ – errors. The $\pm W$, $\pm F$, and $\pm U$ are beyond the scope of this paper and, as stated above, discharge data "provide [an] integrative measure of the continental water balance" (Peterson et al., 2002). One can become acquainted with these components and their magnitude in IPCC-2001 (Church et al., 2001).

Freshwater Inflow from Glaciers

We cannot accurately calculate the meltwater discharge from all panarctic glaciers due to the lack of data. We express glacier contribution as annual, or net mass balance, *b*, which is the difference between mass gain (annual, or net snow accumulation) and mass loss (annual, or net snow-ice ablation) expressed in water equivalent. We used time series from 110 glaciers available in the most recently updated mass balance data set (Dyurgerov, 2002). We grouped glaciers into climatic regions and assumed that glaciers in the same region have similar specific mass balances (Dyurgerov and Meier, 1997; Church et al., 2001; Kuhn et al., 1999). We therefore needed to know only the specific mass balance for several typical glaciers in each region, as well as the total glacier area in the region. The product of these values gives the rate of glacier volume change (ΔVg) in the region. We then summed these values over 3 large regions: the Canadian Arctic Archipelago, Svalbard, and the Russian Arctic. It is difficult to estimate the total error of extrapolating observational data of 110 glaciers to the entire glacier population. According to IPCC-2001 the error in determining glacier volume change over this period is about 30% (Church et al., 2001). The root-mean-squared value calculated for these 110 mass balance time series is about 40%. Glacier volume loss over the last decades has been evident and supported by other sources of information, such as a decrease in glacier area and an increase in equilibrium line altitude, reported from nearly all regions in the Northern Hemisphere (Dyurgerov, 2002).

We also estimated annual volume change for the ice caps around the Greenland ice sheet that are disconnected from the major ice sheet. The surface area of these glaciers is reportedly as large as $70{*}10^3$ km^2 (Weidick and Morris, 1998). We calculated the mass balance of these glaciers as the area-weighted values of the Canadian and Svalbard archipelagoes. We also verified the result of this calculation using several years of mass balance measurements carried out on several Greenland ice caps (Weidick and Morris, 1998). The coefficient of correlation between measured and calculated is 0.63. Using these approximations, we then calculated temporal and spatial changes as well as variability in glacier mass balance.

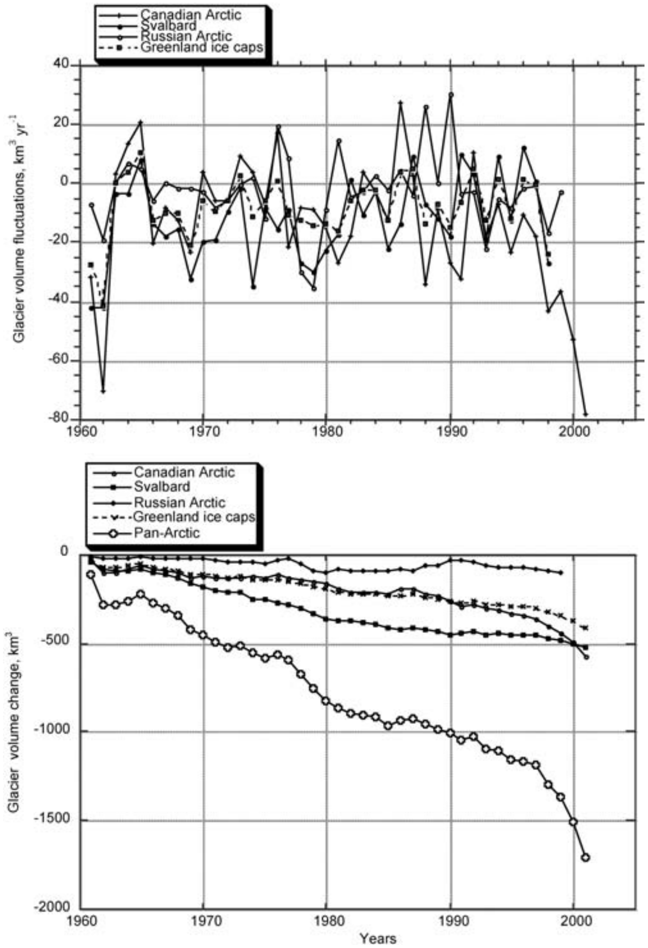

FIGURE 2. (a) Yearly glacier volume change calculated for large arctic archipelagos. (b) Cumulative values over the study period. For Svalbard, values may be overestimated due to our sample bias.

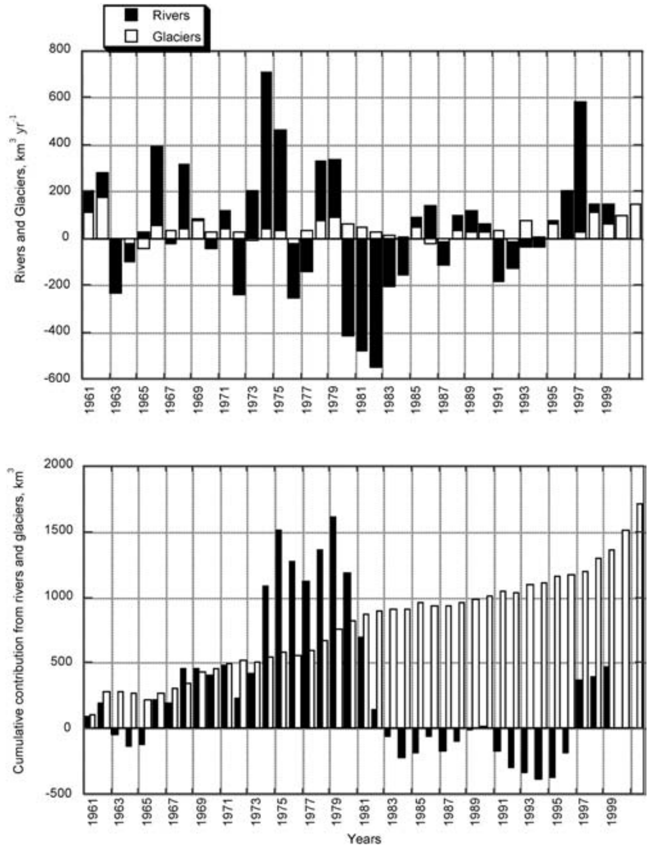

FIGURE 3. (a) Annual net inflow from panarctic rivers and glaciers, not including Greenland Ice Sheet. (b) Cumulative contribution from rivers, glaciers, and both components combined.

Freshwater Inflow from Rivers

We summarized data on annual river discharges for 9 major river basins in the pan-Arctic. We calculated river discharge as the net water inflow: $\Delta Vr = (R_i - \langle R \rangle)$, where R_i is the total annual discharge in year i for 9 major river basins and $\langle R \rangle$ (5282 km^3 yr^{-1}) is the average discharge over the 1961–90 climatic reference period (Fig. 3a). The error in R-value applied to the entire pan-Arctic river basin is about ±5% (Baumgartner and Raichel, 1975, 127).

Results

Volume loss in arctic glaciers is accelerating (Dyurgerov and Meier, 1997; Serreze et al., 2000; Hinzman et al., 2004). Starting around 1960–1976, glaciers show a slightly negative mass balance. The first shift toward accelerating mass loss occurred in 1976–1977 (McCabe et al., 2000). A second, stronger shift started at the end of the 1980s and continues today (Dyurgerov and Meier, 1997; Meier et al., 2003).

Glacier volume change and wastage, while variable (Figs. 2A, 2B), shows a steady increase over the studied period, and values differ by region. We approximated the cumulative net inflow from glaciers relative to other freshwater components delivered to the Arctic Ocean by rivers. Year-by-year glacial inflow is small compared to annual runoff from the main arctic rivers (Fig. 3a). However, the cumulative water inflow from arctic glaciers to the Arctic Ocean exceeds the net inflow of rivers since 1961 (Fig. 3b).

There is no correlation found between the two components. We suppose that their values fluctuate in response to different climatic processes, but during some periods, the coincidence of the extremes resulted in corresponding positive or negative extremes in freshwater pulsation as compared to the average.

We explain the steady increase in glacier inflow by a decrease in ice storage, accelerating ice ablation, and the consistently negative mass balance of arctic glaciers. The increase in glacier volume wastage can be attributed to increased summer air temperature (Eischeid et al., 1995).

River inflow shows a complicated history. The rise up to the end of the 1970s (Fig. 3b) is associated with the generally positive discharge anomalies up to the 1980s, with a sharper decline from 1980 to 1990 essentially due to negative discharge anomalies during much of the 1980s. River discharge anomalies became increasingly positive in the 1990s, but the cumulative river contribution has not yet recovered, so the glacier input dominates. These large changes in river discharge can be explained by the change and multiannual fluctuation of the amount of annual precipitation (Shiklomanov et al., 2002b), the main source of river runoff in panarctic basins.

We calculated annual precipitation in the same manner as net river inflow (the cumulative departure from the 1961–1990 average) using Global Precipitation gridded data (Hulme, 1999). We analyzed these data on two major latitude belts at 50–60°N and 60–70°N, between 117°30′–127°30′W and 32°30′–142°30′E (Fig. 1). Since 1976–1977 the amount of precipitation in these zones has experienced different trends in annual precipitation (Fig. 4). In the 50–60°N belt, there is an increase in the departure from the average. In the 60–70°N belt, an initial strong decrease is followed by an increase that started in the 1990s. This implies that the net river inflow to the Arctic Ocean fluctuates in response to shifts in the annual precipitation on vast areas of Eurasia and North America.

Discussion and Conclusion

The details of our methods differ from those established by Peterson et al. (2002). We used a shorter time series for river runoff in order to allow comparison with the time scale of glacier records and used net water inflow in our calculations in order to make glaciological data comparable with river discharge data. While we confirm the main result of Peterson et al. (2002) that an increase in freshwater inflow to the Arctic Ocean is evident, we also conclude the following:

1. Since the 1990s, freshwater inflow data show substantial and similar patterns of increase from rivers and glaciers. It is likely that this increase is a response to climate warming (glaciers) and an increase in annual precipitation (rivers) in the 50–70°N latitude belt in North America and Eurasia. The largest increase from both components was observed in the 1980s, followed by a strong decrease in net river inflow at the end of the 1980s. Since the beginning of the 1990s, both components show a steady increase. The results of our calculation support the conclusion that the modern hydrographic records have shown a freshening of North Atlantic waters (Bard, 2002). At the same time, Schlosser et al. (2002) came to the opposite conclusion based on the results of an indirect method of determination of freshwater inflow to the ocean by measuring water salinity and $H_2{}^{18}O/H_2{}^{16}O$ ratios in two cross-sections in the Eurasian basin. The authors noted a decrease in river runoff from 1991 to 1996. We can only explain the contradiction between the direct and indirect measurements of water inflow as a result of the complexity of data analysis and interpretation used in the indirect measurements.
2. Freshwater net inflow shows a large fluctuation from both river and glacier components.
3. Cumulative meltwater inflow from glaciers over the 1961–1998 period has exceeded the cumulative inflow from rivers.
4. The rapid increase in freshwater inflow to the Arctic Ocean is consistent with modern hydrographic records, which suggest that deep arctic ventilation has steadily changed over the past 40 yr (Dickson et al., 2002). This freshening and ventilation can be used to model future climate, changes in sea-ice extension, bioproductivity, and other environmental changes in the Arctic.
5. In periods when extremes of both inflow components coincide, the short-term freshwater inflow may be substantial; maximum net inflow was about 750 km^3 in 1974 but was as low as –530 km^3 in 1982 (Fig. 3a). The increase in net inflows may partly explain the change in Earth oblateness (Dickey et al., 2002).

We propose that freshwater inflow to the Arctic Ocean from glaciers will continue to rise. As a result of continuing climate warming, larger areas of glaciers will produce even more freshwater with increasing losses in ice volume. River runoff may also increase, along with continuous glacier contribution, which may cause unforeseen changes in the entire region and further increase convectional circulation and ventilation of deep water in the North Atlantic. These changes need to be monitored in order to develop a long-term environmental strategy. The lack of and continuing decline in observational networks on rivers (Shiklomanov et al., 2002a) and glaciers (Dyurgerov, 2002) in the panarctic region hardly promotes monitoring and forecasting of the arctic water cycle.

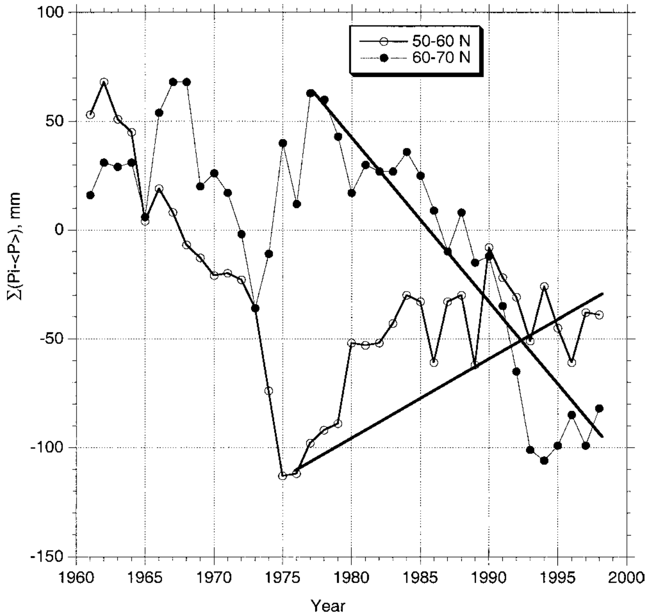

FIGURE 4. Annual precipitation changes through time in watersheds of 9 large panarctic basins (Lammers and Shiklomanov, 2001). Data is in two latitude belts: 50–60°N and 60–70°N, between 117°30′ and 127°30′W and 32°30′ and 142°30′E (Hulme, 1999). Calculations are made as the cumulative, Σ, departures from average values from the 1961–1990 reference period.

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