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Integrated assessment of changes in freshwater inflow to the Arctic Ocean

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[1] We present an integrated and updated quantitative estimation of the river discharge and the meltwater flux and mass contributions from glaciers to the Arctic Ocean and to sea level rise. The average meltwater fluxes from mountain glaciers and ice caps and the Greenland ice sheet have increased markedly, by 56 km^3/yr water equivalent (w.e.) and 160 km^3/yr w.e., respectively, from the period 1961–1992 to the period 1993–2006, reaching in total 700–800 km^3/yr w.e. in 2000–2006. Terrestrial runoff is on the order of 2.4×10^3 km^3/yr and remains significantly larger than the glacier meltwater flux. The terrestrial runoff increase from 1961–1992 to 1993–2006 is 87 km^3/yr, which is small in relative terms, but in absolute terms it is of the same order of magnitude as the meltwater increase from glaciers. The total contribution to sea level rise from glaciers draining to the Arctic Ocean has increased from 0.27 mm/yr (1961–1992) to about 0.64 mm/yr (1993–2006). In some years of the 1993–2006 period, the glacier contribution to sea level rise reached almost 1 mm/yr.

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1. Introduction

[2] The Arctic region contains the largest area of mountain glaciers and ice caps (MG&IC) in the Northern Hemisphere. Amplification in climate and ocean warming, observed in the past decades, has caused enhanced wastage of MG&IC and the Greenland ice sheet (GRIS), increasing the sources of freshwater inflow and causing eustatic sea level rise and changes in water salinity and temperature of the Arctic Ocean (AO) [*Bindoff et al.*, 2007].

[3] Annual terrestrial runoff to the AO from Arctic rivers is significantly larger than the annual freshwater contribution from glaciers [*Peterson et al.*, 2002, 2006]. Even though increasing inflow from rivers is less significant for sea level rise than increasing inflow from glaciers, changes in river inflow magnitude and dynamics are important for the salinity of the AO. The Arctic hydrological drainage basin (AHB) is unique in that the freshwater inflow to the AO from glaciers and rivers can be estimated separately [*Dyurgerov and Carter*, 2004]. Defining three subregions of the AHB makes this clear. In the mainland part of the AHB, which we term the continental circumpolar basin (CCP; Figure 1) and define as the mainland draining directly to the AO, the glacier area is less than 0.04% (primarily in Siberia). In contrast, nearly 2×10^6 km^2 (more than 99%) of the glacier area is in the other two subregions: Greenland (GRIS) and the Arctic polar archipelagos (APAs; Figure 1). From these glaciers, meltwater and icebergs enter into the AO and/or the Arctic seas. In these glacier-dominated parts, there are few gauging stations, and they cover and represent only a small fraction of the watersheds [e.g., Zackenberg basin, northeast Greenland; *Mernild et al.*, 2009a]. Therefore, the glacier mass loss from the Greenland and Arctic archipelagos, in liquid and solid forms, is determined, as a rule, by glaciological methods and modeling [*Dowdeswell and Hagen*, 2004; *Glazovsky and Macheret*, 2006; *Hanna et al.*, 2009; *Box et al.*, 2006].

[4] Previous studies have indicated increased mass losses of MG&IC on a global scale [e.g., *Kaser et al.*, 2006; *Lemke et al.*, 2007; *Meier et al.*, 2007] and of the GRIS [*Rignot et al.*, 2008; *Hanna et al.*, 2008, 2009; *Box et al.*, 2006; *Mernild et al.*, 2009b] during the period 1993–2006. Warming in the Arctic since the mid-1990s is likely to have caused this enhancement of glacier wastage in the AHB. River runoff has also increased during the twentieth century, but this increase has only been studied over longer time periods and has rarely included the past decade [*Peterson et al.*, 2002, 2006; *McClelland et al.*, 2006; *Lemke et al.*, 2007].

[5] Previous studies have indicated significant mass losses from MG&IC and GRIS and changes in terrestrial runoff, but the river changes have never been presented or analyzed jointly with the MG&IC and GRIS changes in the Arctic. A pan-Arctic assessment of the relative and combined changes in components, for the total freshwater inflow into the AO, is thus still lacking. Such an assessment requires an integrated analysis of changes in different glacier and river systems over comparable time periods. In this paper, we used new observational results to quantify, analyze, and

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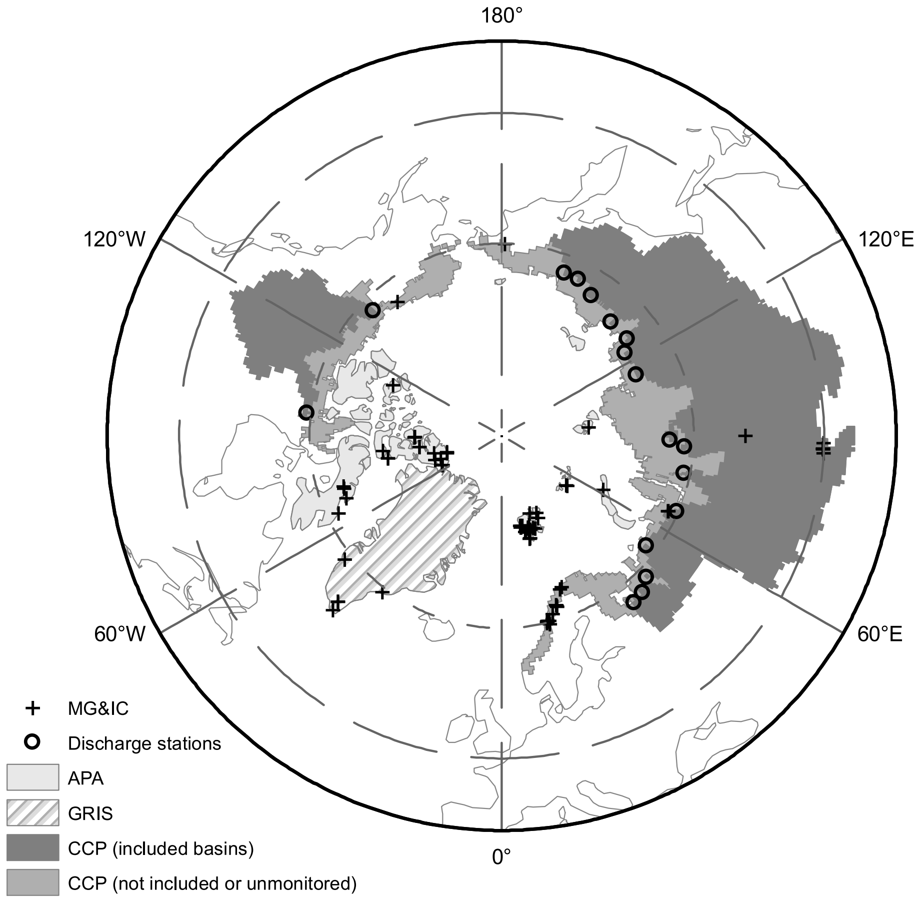

Figure 1. Map of the Arctic Ocean sub-basins GRIS (Greenland), APA (Arctic Polar Archipelagos), and CCP (continental circumpolar basin) used in this study. The measured MG&IC and river drainage basins that were included in the study are also indicated.

synthesize the dynamics of and long-term changes in individual and combined freshwater fluxes into the Arctic Ocean from MG&IC, GRIS, and rivers from the AHB. To quantify the effects of recent changes in the Arctic climate and hydrological systems, we specifically and consistently identified, compared, and analyzed the changes in these systems over the periods 1961–2006, 1961–1992, and 1993–2006. These periods were primarily chosen to highlight changes in glacier systems but were also used consistently for changes in terrestrial runoff even though the driving mechanisms of change are likely to be different and potentially also work on different timescales for river systems. We also estimated the mass balance of MG&IC and GRIS to determine the individual and combined contribution of these glacier systems to eustatic sea level rise.

2. Geographical Settings

[6] The total circumpolar pan-Arctic hydrological basin, AHB, is about 35 × 10^6 km^2 and includes the Arctic Ocean (AO) area of 14.056 × 10^6 km^2; the polar archipelagos and islands, with a combined area of about 3.840 × 10^6 km^2; and Greenland, about 2.175 × 10^6 km^2. Geographically and climatically this is a diverse region that contains the largest glacier area and ice volume after Antarctica.

[7] The glacier extent in the AHB can as mentioned above be divided among three sub-basins: Greenland (GRIS), where the area of the ice sheet and peripheral ice caps is about 1.834 × 10^6 km^2 (81% of Greenland); the APAs, with a glacier area of about 300 × 10^3 km^2 (Table 1); and the drainage area of the CCP, with a 15.83 × 10^6 km^2 total area and 0.043 × 10^3 km^2 glacier area, which is only 0.036% of the land area. For the glacier inflow and mass balance change analysis, we consider the Greenland and APA contributions, which are ungauged. For the river flow analysis, we considered 17 river basins in the CCP (Figure 1), of which 15 are in Eurasia (total basin area of about 10.1 × 10^6 km^2) and 2 are in North America (total basin area of about

Table 1. Total Meltwater Runoff and Total River Runoff Into the Arctic Ocean[a]

	Period		
	1961–2006	1961–1992	1993–2006
MG&IC	163 ± 49 (7)	146 ± 38 (7)	202 ± 48 (13)
MG&IC	163 ± 49 (7)	146 ± 38 (7)	202 ± 48 (13)
GRIS	376 ± 104 (15)	328 ± 58 (10)	488 ± 102 (27)
MG&IC + GRIS	539 ± 140 (21)	473 ± 77 (14)	690 ± 134 (36)
Rivers	2397 ± 130 (19)	2370 ± 129 (23)	2457 ± 115 (31)

[a] Values are in km^3/yr w.e. ± standard deviation, with standard error in parentheses. Standard deviations are sample standard deviations and standard errors were calculated from this measure, by division by the square root of the number of data years.

1.8×10^6 km^2). These 17 river basins represent 75% of the entire area of continental drainage to the Arctic Ocean (78% of Eurasian and 64% of North American drainage areas) and their river runoff is gauged on a regular basis. This runoff also includes a glacier component; however, this component is small and accounts for less than 0.01% of total river discharge to the AO, which comes mostly from the Altai glaciers [*Dyurgerov and Meier*, 2005]. We have not considered any glaciers or rivers that do not contribute fresh water directly to the AO (e.g., those feeding the Bering sea: Alaska, Aleutian Islands, and Kamchatka), even though the fresh water from these regions and ranges does eventually flow farther into the AO through the Bering Strait.

3. Data and Methodology

3.1. Notations

[8] The standard water balance for land is given by the equation

$$dW/dt = P - E - R, \tag{1}$$

where P is the rate of precipitation, E is the rate of evapotranspiration, R is the rate of surface water runoff, and dW/dt is the change of storage in liquid and solid forms; all these terms are expressed in water equivalent (w.e.) per year. The change in storage can also be expressed as

$$dW/dt = M + F + B + U + \delta,$$

where M is the change in soil moisture content and groundwater storage (of liquid or seasonally frozen water), F is the change in permafrost storage (permanently frozen water), B is the change in ice storage on land surface (or glacier mass balance), U is the change in anthropogenic water abstraction, and δ represents random errors. The present glacier change analysis is restricted to glaciers, excluding the surrounding drainage basins and subglacial ground, which implies that we omit the terms M, F, and U and focus on the quantification of the B and associated δ terms. In the remote and largely glacierized APA and GRIS sub-basins, we expect these components to be small, particularly in relation to B, whereas they may be larger in the extensive river drainage basins in the CCP. However, in this study we do not attempt to separate and quantify all components of the water balance in hydrological drainage basins. Such an effort requires more detailed modeling and analysis at the basin scale, which is beyond our scope of quantifying freshwater inflow to the Arctic Ocean; therefore, we use direct measurements of river discharge at the most downstream locations. For glacier systems, we adapt equation (1) to determine the total annual glacier runoff and the part of this runoff that contributes to eustatic sea level change:

$$R = P - E - dW/dt = P - E - B + \delta, \tag{2}$$

where B = SMB + D is the total mass balance, expressing the change of ice storage as the sum of the surface mass balance (SMB) and the dynamic mass balance (D). The latter component, D, equals the ice mass discharging through the grounding line. The grounding line separates the grounded ice from that floating in water. The D component is substantial for glaciers terminating in water, as in the coastal areas of Greenland and the Arctic ice caps [e.g., *Glazovsky and Macheret*, 2006; *Burgess and Sharp*, 2008; *Dowdeswell et al.*, 2008; *Rignot et al.*, 2008]. Under equilibrium conditions (SMB + D = 0), $R = P - E$.

[9] In the following, we use these water balance expressions and notations for investigations of the three sub-basins, GRIS, APA, and CCP. Application of equation (1) to glaciers must include SMB + D data, which are crucially important for the GRIS and APA sub-basins, but these two quantities are negligible for the CCP sub-basin. All balance (SMB and D) results are given in water-equivalent units to be comparable with runoff.

3.2. Mass Balance of MG&IC

[10] We used the results of annual direct mass balance observations, carried out on several dozens of MG&IC, for the 1961–2006 period [*Dyurgerov and Meier*, 2005; *Glazovsky and Macheret*, 2006; *Flunctuations of Glaciers* (*FoG*), 2008]. Only limited data are available after 2006. We made separate calculations of the mass balance change rates for the two subperiods 1961–1992 and 1993–2006, which have substantially different conditions of climate and related mass balance characteristics [*Lemke et al.*, 2007]. We further used annual glacier area change, defined as the change of "conventional" glacier area [*Elsberg et al.*, 2001; *Dyurgerov*, 2008], for calculating the annual mass balance weighted by the glacier area of the mountain regions and the ice caps they have represented, as described by *Dyurgerov and Meier* [2005] (updated in 2009). The mass balance for any particular year is thus tied to the glacier area for that particular year. The method of mass balance measurements and calculations is given by *Østrem* and *Brugman* [1991], *Fountain et al.* [1997], and *Kaser et al.* [2003]. Specific details of the upscaling approach of mass balance time series from individual glaciers to larger regions are given by *Dyurgerov and Meier* [2005] and *Kaser et al.* [2006].

[11] The glacier area data used here were taken from many sources, primarily from national glacier inventories (e.g., Former Soviet Union, Scandinavia and Global Inventory, and World Glacier Monitoring Service [*Haeberli et al.,* 1989]). It is important to coordinate the use of mass balance observational data consistently with area change data. Area change was calculated for every individual glacier where mass balance observations were carried out for any year in the 1961–2006 period [*Dyurgerov and Meier*, 2005] (updated in 2009). To obtain annual rate of glacier area change, we used linear interpolations between areas determined from repeated measurements based on topographical maps and comparisons with airborne and satellite images.

3.3. Greenland Ice Sheet Mass Balance

[12] For the purposes of our study, we used the most recent results of the GRIS mass balance studies [*Rignot et al.*, 2008; *Hanna et al.*, 2008, 2009; *Box et al.*, 2006; *Mernild et al.*, 2009b].

[13] The GRIS mass balance was substantially negative during 1960–2006 [*Rignot et al.*, 2008]. SMB was determined by two independent model calculations [*Hanna et al.*, 2008; *Box et al.*, 2006] and applied to different parts of the GRIS. SMB was calculated for 34 drainage units of the entire Greenland ice sheet [*Rignot et al.*, 2008, Figure 1].

The ice discharge component was calculated for the same 34 units using measurements of surface velocity and ice thickness at flux gates located 10–20 km upstream of the ice front. Several assumptions were made to acquire spatially and temporally resolved ice velocity and thickness measurements [*Rignot et al.*, 2008]. The B_{GRIS} rate average for the ice sheet changed from −110 ± 70 km^3/yr w.e. in the 1960s–1970s to −30 ± 50 km^3/yr w.e. in the 1970s–1980s and −97 ± 47 km^3/yr w.e. in 1986–1996. Acceleration in mass losses increased around the mid-1990s and the mass deficit tripled to −267 ± 38 km^3/yr w.e. in 2007. *Rignot et al.* [2008] calculated annual B_{GRIS} using linear regression with high correlation between anomalies of $\mathrm{SMB}_{\mathrm{GRIS}}$ (averaged for 3 years) and the D component. For the purpose of our study we used the B_{GRIS} rate from the study by *Rignot et al.* [2008] for the aforementioned periods. However, we applied a simpler interpolation scheme, segmented to follow the pattern of values just listed, to get annual B_{GRIS} values: constant annual rates for the 1960s–1970s and 1970s–1980s and linear interpolation between 1980 and 1986, between 1987 and 1996, and between 1997 and 2007.

3.4. Calculation of Total Runoff From the Greenland Ice Sheet and MG&IC

[14] According to equation (2), we have to know $P - E$ to get R. Annual precipitation data are very rarely available in glaciology. To obtain $P - E$ for Greenland, we used the annual amount of net precipitation calculated for the GRIS by *Hanna et al.* [2008] and cordially given to Dyurgerov in digital form. From $(P - E)_{\mathrm{GRIS}}$ and B_{GRIS} we calculated $R_{\mathrm{GRIS}} = B_{\mathrm{GRIS}} + (P - E)_{\mathrm{GRIS}}$.

[15] Only limited precipitation data or annual snow accumulation data are available for MG&IC in APA and CCP sub-basins. To estimate the MG&IC total water fluxes, $R_{\mathrm{MG\&IC}}$, we did not use precipitation data for these areas but instead used the ratio $R_{\mathrm{GRIS}}/(P - E)_{\mathrm{GRIS}}$, and applied this ratio to the $\mathrm{SMB}_{\mathrm{MG\&IC}}$, using observational data of $\mathrm{SMB}_{\mathrm{APA}}$ and $\mathrm{SMB}_{\mathrm{CCP}}$ [*Dyurgerov and Meier*, 2005] (updated in 2009).

[16] We made another adjustment to determine the D component, because it is important for the APA sub-basin, where the area of ice caps is large with many outlets and tongues discharging into the coastal waters of Arctic seas. Direct observations, based on repeated laser altimetry, interferometry, and radio-echo sounding, and comparative analysis of topographic maps, aerial photography, and space images, are available for several ice caps and regions (e.g., the Devon ice cap [*Burgess and Sharp*, 2008], Bylot Island [*Dowdeswell et al.*, 2007], the Queen Elizabeth Islands [*Abdalati et al.*, 2004], Svalbard [*Dowdeswell et al.*, 2008], and Russian archipelagos [*Glazovsky and Macheret*, 2006]). From these data we determined an adjustment factor of 1.3, the average of the values obtained for these five regions. This factor was applied to SMB to get B_{APA}. We did not apply this adjustment to the CCP sub-basin because the glacier area is very small there and virtually no glaciers terminate in water.

3.5. River Runoff

[17] To estimate the river inflow to the AO, we gathered and assembled discharge data for all 17 rivers with average discharge above 10 km^3/yr in the CCP. Together, these rivers compose 75% of the CCP area and 74% of the discharge contributing directly to the AO.

[18] Monthly discharge data were gathered from the Water Survey of Canada (HYDAT, http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=main_e.cfm) for the two included Canadian rivers, from the Arctic Rapid Integrated Monitoring System (ArcticRIMS, http://rims.unh.edu) for 14 of the 15 included Russian rivers, and from the Regional Hydrometeorological Data Network for the Pan-Arctic Region (R-ArcticNET, http://www.r-arcticnet.sr.unh.edu) [*Lammers et al.*, 2001] for 1 Russian river. For rivers with incomplete records, data from hydrological stations farther upstream were correlated with the data series of the downstream station to extend and complete the time series (R^2 ranging from 0.68 to 0.99). In all cases, only years with complete data for all months of the year were included.

[19] To estimate missing data for particular rivers and years (comprising ~9% of all flow-weighted yearly data points), we used a subset of 6 years, with complete data for all rivers, to normalize each river discharge according to the average relative influence on the total annual discharge to the AO. The relative contributions of the 17 rivers to the total discharge remained almost constant. (The flow-weighted standard deviation of the weights for all rivers during the 6-year subset was ~0.012, on a unitless scale from 0 to 1.) These normalized weights were then used to estimate values of missing data for a particular river and year. Total annual fluxes for each year and for the periods 1961–2006, 1961–1992, and 1993–2006 were then estimated. We did not compensate for the effect of dams in this analysis because the dam impacts have been shown to be limited in syntheses based on annual data for the region [*McClelland et al.*, 2006].

4. Results and Discussion

4.1. Total Freshwater Fluxes From Glaciers and Rivers

[20] Over the period 1961–2006, the total flow from rivers has remained almost an order of magnitude larger than the total flows from MG&IC and GRIS (Figure 2a and Table 1). However, since the mid-1990s, a significant increase in total flow is evident for both MG&IC and GRIS, but in particular for GRIS (Figure 2a). In relative terms, the changes in total flow for the period 1993–2006 compared to that for 1961–1992 amount to +39%, +49%, and +4% for MG&IC, GRIS, and rivers, respectively. In terms of absolute anomalies, the increase in river runoff from 1961–1992 to 1993–2006 (+87 km^3/yr) is of the same order of magnitude as the increase in total freshwater flow from the MG&IC and GRIS over the same period (+56 km^3/yr w.e. and +160 km^3/yr w.e., respectively; see Figure 2b). The interannual variability, however, is much larger in the river than in the glacial runoff, although the assumption of constant or linearly changing SMB+D for GRIS implies that the variability in total glacier runoff is understated.

4.2. MG&IC and GRIS Contributions to Sea Level Change

[21] Figure 3 summarizes the evolution over 1961–2006 of the mass balance (SMB and D) of the MG&IC and GRIS. The mass loss from GRIS dominated over the losses from MG&IC during all periods except in the late 1970s and early

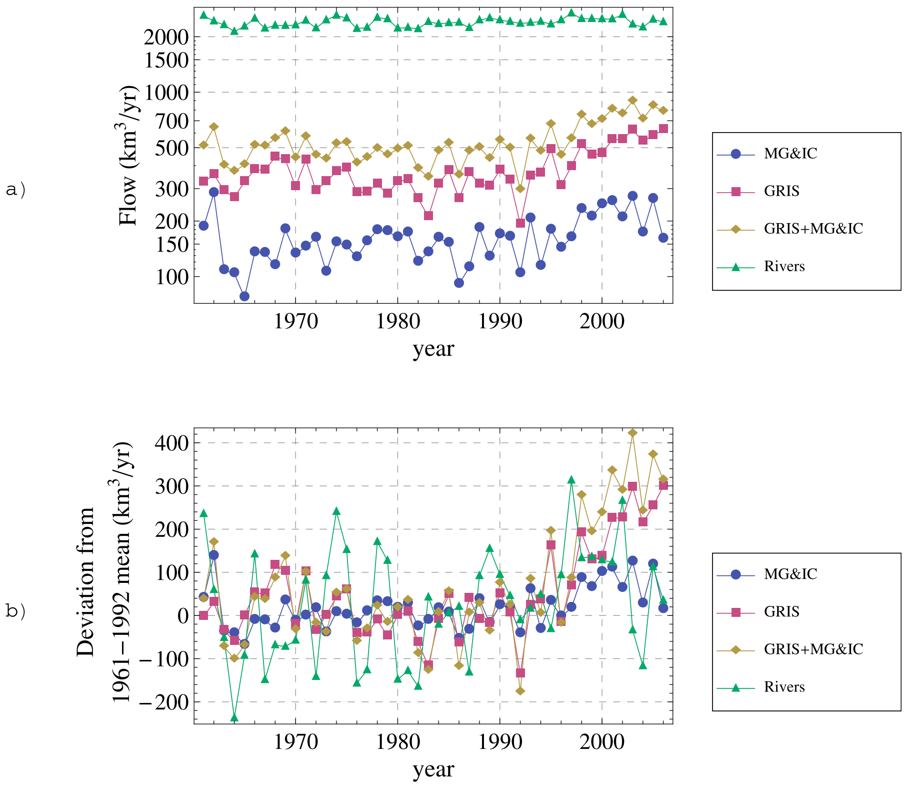

Figure 2. (a) Total annual freshwater flows from MG&IC, GRIS, and rivers (km^3/yr, logarithmic scale); (b) annual freshwater flows from MG&IC, GRIS, and rivers (km^3/yr) as deviation from average values for 1961–1992.

1980s, when losses were of equal magnitude and in some years greater from MG&IC than from GRIS. Since the mid-1990s, however, mass losses from GRIS have increased significantly and are dominating the Arctic contribution of glacial meltwater to sea level rise. The rate of loss from MG&IC and GRIS increased by +52 and +85 km^3/yr w.e., respectively, between the periods 1961–1992 and 1993–2006 (Table 2). In the case of GRIS, this constitutes more than double the mass loss rate during 1993–2006 compared with the 1961–1992 period. Accumulated over the period 1961–2006, the mass losses from Arctic MG&IC and GRIS have contributed ~6300 km^3 w.e. to the global oceans. More than half of this was added after 1992 (Table 2). Translated into sea level rise, the MG&IC and GRIS contribution to the ocean has increased dramatically and reached 0.75–0.97 mm/yr in 2000–2006 (Figure 4).

[22] The increases found in meltwater production by the GRIS and MG&IC are associated with the Arctic amplification of recent global climate warming [*Stroeve et al.*, 2007; *Hanna et al.*, 2008] and the decline in sea-ice extent over the past decades, which accelerated in the first decade of the 21st century. Arctic amplification implies that the rise in surface air temperature, in response to increasing atmospheric greenhouse gas concentrations, is larger in the Arctic than in the world as a whole. As the climate warms, the summer melt season lengthens and intensifies, leading to increased melt areas in GRIS and MG&IC [*Mernild et al.*, 2009b], increased meltwater runoff, and decreased (more negative) SMB [*Hanna et al.*, 2008]. The glacier surface velocity increases because of lubrication of bottom ice [*Zwally et al.*, 2002; *Rignot and Kanagaratnam*, 2006]. The ice discharge through the grounding line increased for several of the largest Greenland outlets [*Rignot et al.*, 2008]. The direct effect of oceanic water warming [*Hanna et al.*, 2009] may further lead to increased basal melting and iceberg calving in coastal areas of GRIS, Svalbard, and the Russian and Canadian Arctic [e.g., *van de Wal et al.*, 2008; *Rignot et al.*, 2008; *Pfeffer et al.*, 2008].

4.3. Uncertain River Runoff Contribution to Sea Level Change

[23] Regarding the possible contribution range of the river runoff increase to sea level rise, the lowest-limit case is that the increase of R in water balance equation (1), applied to the river basin systems, is entirely explained by a corresponding increase in $P - E$. This case implies unchanged water storage in the river basins (i.e., $dW/dt = 0$) and consequently zero river contribution to sea level rise. The upper limit case is that $P - E$ has remained essentially unchanged in the basins. The R increase must then be explained by a corresponding decrease, $M + F < 0$, in soil moisture content, groundwater storage, and/or permafrost storage in the river basins. In this case, the entire river runoff increase would contribute to sea level rise. For both these extreme cases, no change in U is assumed. In reality, the sea level rise contribution from the river R increase is likely to be somewhere in between these two limiting cases and to be a combination of changes in $P - E$ and $M + F$, with different relative importance in different geographical regions [*Adam and Lettenmaier*, 2008].

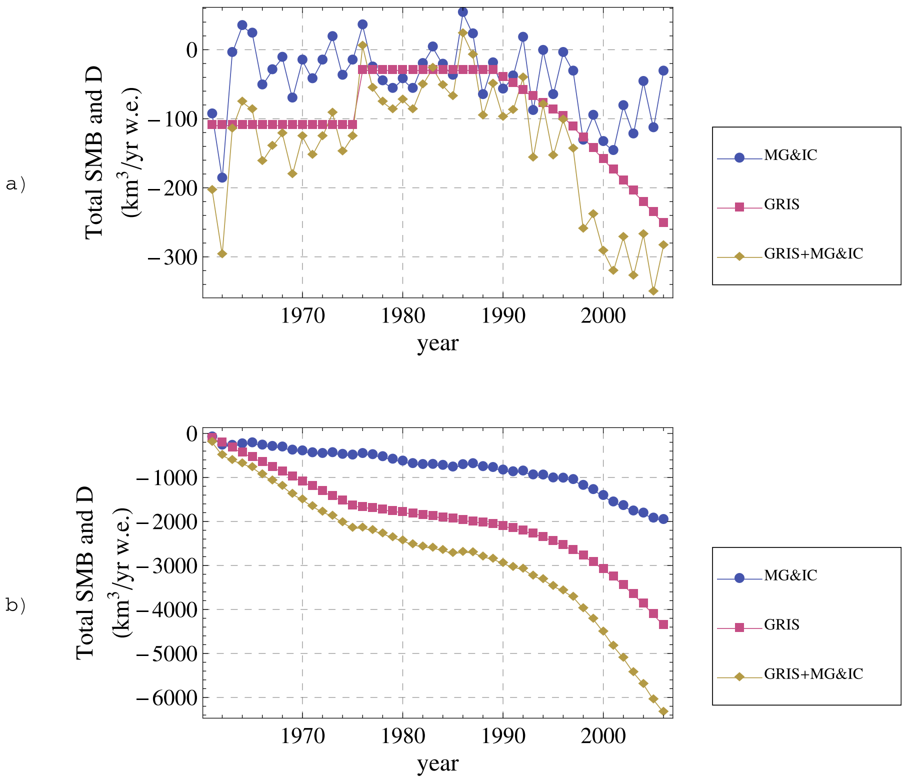

Figure 3. (a) Total annual mass balances (surface plus dynamic components, in water equivalent) of the Greenland ice sheet, the mountain glaciers, and the polar ice caps, and the sum of all over the period 1961–2006; (b) same as in Figure 3a in terms of cumulative mass balances.

[24] Several studies have identified increases in poleward moisture transport, which imply that precipitation P has increased and may be a main driver of increasing river runoff in the Arctic [*Dyurgerov and Carter*, 2004; *McClelland et al.*, 2004, 2006]. However, observations of P are prone to bias [*Rawlins et al.*, 2006] and cannot fully explain the observed river runoff trends [*Berezovskaya et al.*, 2004; *Milliman et al.*, 2008]. Furthermore, it is neither directly measurable nor readily evident how the other essential component in the $P - E$ water balance term (i.e., the evaporation E) has changed over the same period in the Arctic river basins. Assessment of the possible changes in E and the water storage term $dW/dt = \pm M \pm F$ requires further basin-specific investigations and modeling, which are outside the scope of the present study. Nevertheless, this study has shown that such investigations are indeed needed and worthwhile. Quantifying the river R change consistently and comparing it with corresponding MG&IC and GRIS changes have demonstrated that these three components together contribute significantly to increasing freshwater inflow into the AO and to sea level rise.

[25] With regard to the dW/dt term in the river basins, other recent studies have indicated that it may be significantly nonzero because of both ongoing permafrost thawing [*Adam and Lettenmaier*, 2008; *Lyon et al.*, 2009; *Lyon and Destouni*, 2010] and increasing groundwater flow into rivers in Arctic and subarctic basins [*Smith et al.*, 2007]. New analysis of land water storage from Gravity Recovery and Climate Experiment satellite data also indicates negative dW/dt terms for some major Arctic basins, although data are as yet available only for a few years [*Ramillien et al.*, 2008]. The changes in fire frequency and dam construction may also contribute to river runoff changes, but these factors cannot realistically explain the full extent of the observed increase in river runoff [*McClelland et al.*, 2004].

[26] The increase in terrestrial runoff found herein is in general agreement with similar increases found in earlier studies [e.g., *Peterson et al.*, 2002, 2006; *Dyurgerov and Carter*, 2004; *McClelland et al.*, 2006]. However, the present study shows a lower rate of change (+2.7 km^3 yr^{-2} over 1961–2006) than a similar past study, which found an increase of +5.6 km^3 yr^{-2} during 1964–2000 for a slightly

Table 2. Total Mass Balance of MG&IC and GRIS[a]

Period	1961–2006	1961–1992	1993–2006
MG&IC	43 ± 52 (8) [1971]	27 ± 45 (8) [869]	79 ± 49 (14) [1102]
GRIS	95 ± 61 (9) [4368]	69 ± 39 (7) [2217]	154 ± 61 (16) [2151]
MG&IC + GRIS	138 ± 95 (14) [6339]	96 ± 64 (11) [3086]	233 ± 88 (25) [3253]

[a] Values are in km^3/yr w.e. ± standard deviation, with standard error in parentheses and cumulative values in brackets.

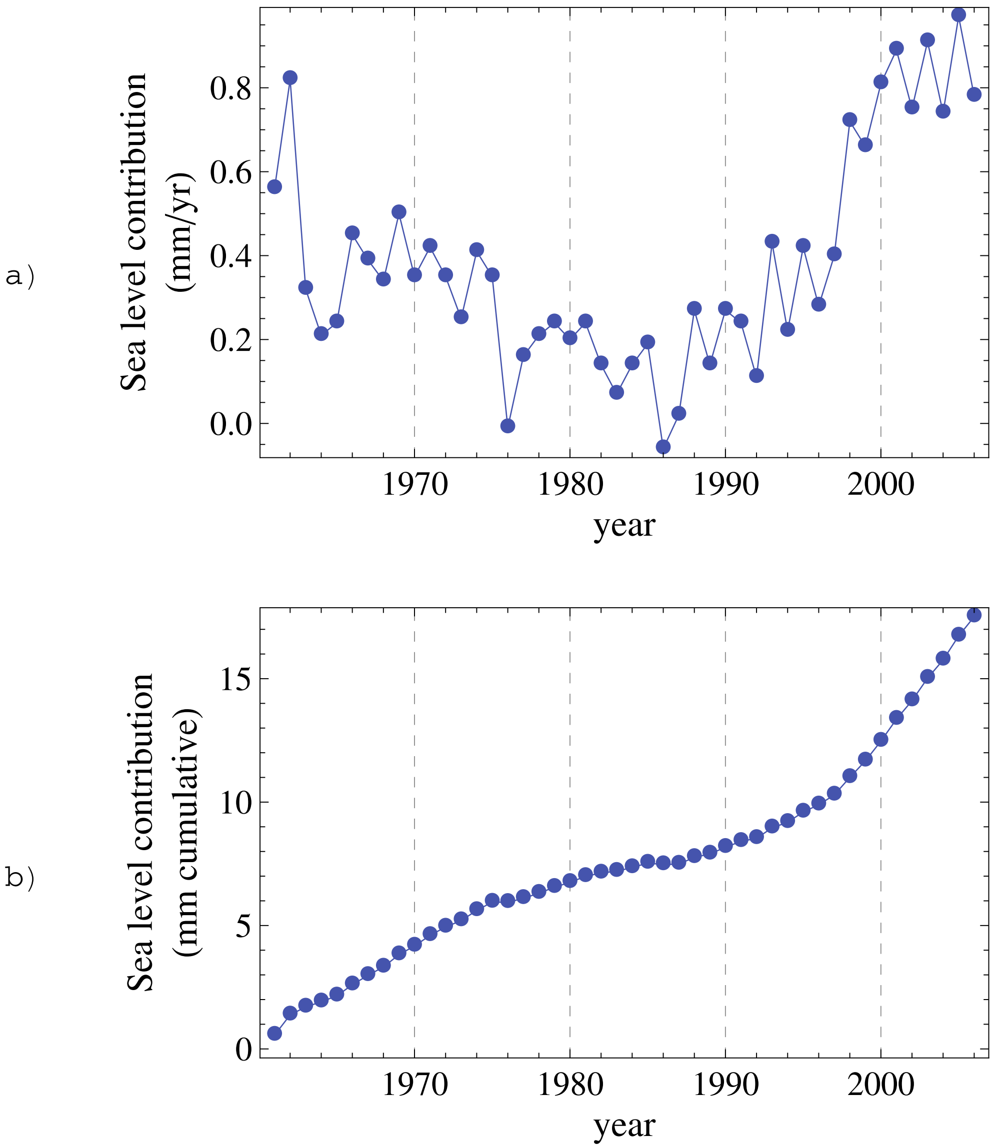

Figure 4. (a) Year-by-year contribution from GRIS and MG&IC to sea level change in the ocean; (b) same as in Figure 4a in cumulative values.

larger area [*McClelland et al.*, 2006]. The main reason for these differences is that the present analysis covers a longer period of time, including both the particularly low discharge values in 2003 and 2004 and the relatively high values in the early 1960s (Figure 2). The present analysis, when applied to the 1964–2000 period studied by *McClelland et al.* [2006], gives a trend of +5.1 km^3 yr^{-2}. The remaining difference may be attributable to the inclusion by *McClelland et al.* [2006] of a set of smaller rivers, where discharge had increased more rapidly than from the larger rivers.

4.4. Other Major Uncertainties

[27] It is hardly possible to account for and estimate all the sources of uncertainty that may be associated with different assumptions, simplifications, direct measurements, and models. Nevertheless, in this study we outline and exemplify several sources. The surface mass balance [*Hanna et al.*, 2009] and the *D* component [*Rignot et al.*, 2008] of the GRIS and ice caps in the Arctic remain major sources of uncertainty in the estimation of freshwater fluxes and eustatic sea level rise. The ice discharge through the grounding lines of large outlet glaciers in Arctic archipelagos is also still poorly known. The iceberg calving and basal melting of floating ice has been estimated only roughly and in few places in the Russian and Canadian Arctic archipelagos and in Svalbard [*Dowdeswell and Hagen*, 2004; *Burgess et al.*, 2005; *Hagen et al.*, 2003]. The dynamic mass balance component is highly variable in time [*Rignot et al.*, 2008]; however, in this study it was taken as constant, a necessary simplification. The application of the GRIS data to MG&IC for estimating the runoff is also a source of uncertainty, the magnitude of which we cannot estimate here.

[28] Meltwater runoff from GRIS and MG&IC in the Arctic may be overestimated because of neglect of internal accumulation in some models, mostly from meltwater retention in porous firn layers. These effects may constitute from 10% to more than 80% of annual precipitation (snow

accumulation) in the Arctic [*Bahzev*, 1980, *Trabant and Mayo*, 1984]. The amount varies spatially and temporally, depending on the temperature in the ice column. These processes lead to increases of snow and firn density and overestimation of meltwater runoff. The increase of snow density in Greenland may have been overestimated by 26%, resulting in a 32% increase in internal accumulation [*Parry et al.*, 2007].

[29] The spatial extrapolation of observed mass balances from measured glaciers to the rest of the glacier population may be one of the largest sources of uncertainty. A recently developed and applied interpolation scheme to calculate regional and global mass balances [*Cogley*, 2004] may lead to less uncertain results, but it requires a comparison with independent sources of information (e.g., laser altimetry).

[30] With regard to river runoff, previous studies concluded that its trends are largely similar across small and large Arctic basins and across latitudinal belts [*McClelland et al.*, 2006] and that differences in estimates of total runoff into the AO vary relatively linearly with the contributing drainage area included in the analysis [*Prowse and Flegg*, 2000]. This finding indicates that the discharge changes identified for the basins in this study should also be representative of discharge changes in the unmonitored 24% of the CCP, which was not included in the present analysis. However, it is advised to use caution in extrapolating results to ungauged areas, because several hydrologically relevant characteristics show significant bias between monitored and unmonitored areas [*Bring and Destouni*, 2009].

5. Conclusions

[31] We have presented an integrated and updated quantitative estimate of the river runoff, and the meltwater flux and mass contributions from glaciers, to the Arctic Ocean and to sea level rise. During the recent period 1993–2006, the meltwater fluxes from MG&IC and GRIS have increased markedly from their average values during 1961–1992. River inflow remains the major component of freshwater inflow from land to the Arctic Ocean. Even though the river flow increase during 1993–2006 is small in relative terms, in absolute terms it is of the same order of magnitude as the meltwater increase from glaciers.

[32] The total glacier contribution to the ocean has increased from 0.27 mm/yr (1961–1992) to about 0.64 mm/yr (1993–2006). In some years, the glacier contribution to sea level rise reached almost 1 mm/yr. The river flow contribution to sea level rise is also potentially significant, but it remains highly uncertain and debated. Further investigations and assessments of evaporation and water storage (permafrost, soil water, and groundwater) changes within the Arctic river basins are needed.

[33] In some years during the 1961–2006 period, the Arctic mountain glaciers and ice caps dominated over Greenland as contributors to sea level rise. However, since the mid-1990s, the amount of surface melting and the dynamic mass balance component have tripled for the Greenland ice sheet, which has now surpassed the mountain glaciers as the largest contributor to sea level rise. The total mass balance of GRIS was negative from 1961 until 2006. The water fluxes to the Arctic Ocean from both GRIS and MG&IC reached 700–800 km^3/yr w.e. in 2000–2006, increasing in significance beside the still dominating inflows from major river systems on the order of 2.4 × 10^3 km^3/yr.

[34] The recent increasing temperatures are most likely the main driver of the decreasing glacier mass in the Arctic. Therefore, a continued future strong warming in the Arctic may lead to further increased importance of glacier meltwater relative to river discharge. However, the latter may also be affected by increasing permafrost thawing caused by the warming trend; together, the considerable total glacier meltwater and river runoff increases affect the salinity, temperature, and water circulation and thus the whole Arctic Ocean environment.

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References

Abdalati, W., W. Krabill, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, J. Yunel, and R. Koerner (2004), Elevation change in the ice caps in the Canadian Arctic Archipelago, *J. Geophys. Res.*, *109*, F04007, doi:10.1029/2003JF000045.

Adam, J. C., and D. P. Lettenmaier (2008), Application of new precipitation and reconstructed streamflow products to streamflow trend attribution in northern Eurasia, *J. Clim.*, *21*, 1807–1828.

Bazhev, A. B. (1980), Methods of determining the internal infiltration accumulation of glaciers (in Russian), *Data Glaciol. Stud.*, *39*, 73–81.

Berezovskaya, S., D. Yand, and D. L. Kane (2004), Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds, *Geophys. Res. Lett.*, *31*, L21502, doi:10.1029/2004GL021277.

Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley, and A. Unnikrishnan (2007), Observations: Oceanic climate change and sea level, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Cambridge Univ. Press, Cambridge, U. K.

Box, J. E., D. H. Bromwich, B. A. Veenhuis, L.-S. Bai, S.-H. Wang, J. C. Stroeve, T. Haran, J. C. Rogers, and K. Steffen (2006), Greenland ice sheet surface mass balance variability (1988–2004) from calibrated Polar MM5 output, *J. Clim.*, *19*(12), 2783–2800.

Bring, A., and G. Destouni (2009), Hydrological and hydrochemical observation status in the pan-Arctic drainage basin, *Polar Res.*, *28*, 327–338, doi:10.1111/j.1751-8369.2009.00126.x.

Burgess, D. O., and M. J. Sharp (2008), Recent changes in thickness of the Devon Island ice cap, Canada, *J. Geophys. Res.*, *113*, B07204, doi:10.1029/2007JB005238.

Burgess, D. O., M. J. Sharp, D. W. F. Mair, J. A. Dowdeswell, and T. J. Benham (2005), Flow dynamics and iceberg calving rates of Devon Ice Cap, Nunavut, Canada, *J. Glaciol.*, *51*, 219–230.

Cogley, J. G. (2004), Greenland accumulation: An error model, *J. Geophys. Res.*, *109*, D18101, doi:10.1029/2003JD004449.

Dowdeswell, E. K., J. A. Dowdeswell, and F. Cawkwell (2007), On the glaciers of Bylot Island, Nunavut, Arctic Canada. *Arct. Antarct. Alp. Res.*, *39*(3), 402–411, doi:10.1657/1523-0430(05-123).

Dowdeswell, J. A., and J. O. Hagen (2004), Arctic glaciers and ice caps, in *Mass Balance of the Cryosphere: Observations and Modeling of Contemporary and Future Changes*, edited by J. Bamber and A. Payne, pp. 527–558, Cambridge Univ. Press, Cambridge, U. K.

Dowdeswell, J. A., T. J. Benham, T. Strozzi, and J. O. Hagen (2008), Iceberg calving flux and mass balance of the Austfonna ice cap on Nordaustlandet, Svalbard, *J. Geophys. Res.*, *113*, F03022, doi:10.1029/2007JF000905.

Dyurgerov, M. B. (2008), Glacier mass balance: Results from direct observations (abstract), paper presented at the International Workshop on Mass

Balance Measurements and Modelling, Skeikampen, Norway, 26–28 March, 50A092.

Dyurgerov, M. B., and C. L. Carter (2004), Observational evidence of increases in freshwater inflow to the Arctic Ocean, *Arct. Antarct. Alp. Res.*, *36*(1), 117–122.

Dyurgerov, M. B., and M. F. Meier (2005), Glaciers and the changing Earth system: A 2004 snapshot, *Occas. Pap.*, *58*, 117 pp., Inst. of Arct. and Alp. Res., Boulder, Colo. (http://instaar.colorado.edu/other/occ_papers.html)

Elsberg, D. H., W. H. Harrison, K. A. Echelmeyer, and R. M. Krimmel (2001), Quantifying the effects of climate and surface change on glacier mass balance, *J. Glaciol.*, *47*(159), 649–658.

Fluctuations of Glaciers (FoG) 2000–2005 (2008), *ICSU(CCS)-UNEP-UNESCO 2008*, vol. IX, World Glacier Monit. Serv., Zurich.

Fountain, A., R. M. Krimmel, and D. Trabant (1997), A strategy for monitoring glaciers, *U.S. Geol. Surv. Circ. 1132*, 1–19.

Glazovsky, A. F., and Y. Y. Macheret (2006), Evraziyskaya Arktika, in *Oledenenie Evrazii v proshlom, nastoyashchem i blizhayshem budushchem*, vol. 1, edited by V. M. Kotlyakov, chap. 4, pp. 97–114, Nauka, Moscow.

Haeberli, W., H. Bosch, K. Scherler, G Østrem, and C. C. Wallén (Eds.) (1989), World Glacier Inventory-Status 1988, *IAHS (ICSI)/UNEP/UNESCO (1989)*, 290 pp., World Glacier Monit. Serv., Paris.

Hagen, J., K. Melvold, F. Pinglot, and J. Dowdeswell (2003), On the net mass balance of the glaciers and ice caps in Svalbard, Norwegian Arctic, *Arct. Antarct. Alp. Res.*, *35*, 264270 doi:10.1657/1523-0430(2003)035[0264:OTNMBO]2.0.CO;2.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffits (2008), Increased runoff from melt from the Greenland ice sheet: A response to global warming, *J. Clim.*, *21*, 331–341, doi:10.1175/2007JCLI1964.1.

Hanna, E., J. Cappelen, X. Fettweis, P. Huybrechts, A. Luckman, and M. H. Ribergaard (2009), Hydrologic response of Greenland ice sheet: The role of oceanographic warming, *Hydrol. Processes*, *23*, 7–30, doi:10.1002/hyp.7090.

Kaser, G., A. Fountain, and P. Jansson (2003), A manual for monitoring the mass balance of mountain glaciers, *IHP-VI Tech. Doc. Hydrol. 59*, UNESCO, Paris.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, *Geophys. Res. Lett.*, *33*, L19501, doi:10.1029/2006GL027511.

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, B. M. Fekete, and B. J. Peterson (2001), Assessment of contemporary Arctic river runoff based on observational discharge records, *J. Geophys. Res.*, *106*, 3321–3334.

Lemke, P., J. Ren, R. B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R. H. Thomas, and T. Zhang (2007), Observations: Changes in snow, ice and frozen ground, in *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, pp. 337–383, Cambridge Univ. Press, Cambridge, U. K.

Lyon, S., and G. Destouni (2010), Changes in catchment-scale recession flow properties in response to permafrost thawing in the Yukon River Basin, *Int. J. Climatol.*, doi:10.1002/joc.1993.

Lyon, S. W., G. Destouni, R. Giesler, C. Humborg, M. Mörth, J. Seibert, J. Karlsson, and P. A. Troch (2009), Estimation of permafrost thawing rates in a sub-Arctic catchment using recession flow analysis, *Hydrol. Earth Syst. Sci. 13*, 595–604.

McClelland, J. W., R. M. Holmes, B. J. Peterson, and M. Stieglitz (2004), Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change, *J. Geophys. Res.*, *109*, D18102, doi:10.1029/2004JD004583.

McClelland, J. W., S. J. Déry, B. J. Peterson, R. M. Holmes, and E. F. Wood (2006), A pan-arctic evaluation of changes in river discharge during the latter half of the 20th century, *Geophys. Res. Lett. 33*, L06715, doi:10.1029/2006GL025753.

Meier, M. F., M. B. Dyurgerov, U. K. Rick, S. O'Neel, W. T. Pfeffer, R. S. Andersson, S. P. Andersson, and A. F. Glazovsky (2007), Glaciers dominate eustatic sea-level rise in the 21st century, *Science*, *317*, 1064–1067, doi:10.1126/science.1143906.

Mernild, S. H., G. E. Liston, and B. Hasholt (2009a), Record Greenland ice sheet surface melt extent and runoff, *Eos Trans. AGU*, *90*(2), 13, doi:10.1029/2009EO020002.

Mernild, S. H., G. E. Liston, C. A. Hiemestra, K. Steffen, E. Hanna, and J. H. Christensen (2009b), Greenland Ice Sheet surface mass-balance modeling and freshwater flux for 2007, and in a 1995–2007 perspective, *Hydrol. Processes*, *23*, 2470–2484, doi:10.1002/hyp.7354.

Milliman, J. D., K. L. Farnsworth, P. D. Jones, K. H. Xu, and L. C. Smith (2008), Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000, *Global Planet. Change*, *62*, 187–194, doi:10.1016/j.gloplacha.2008.03.001.

Østrem, G., and M. Brugman (1991), Glacier mass-balance measurements: A manual for field and office work, *NHRI Sci. Rep. 4*, 224 pp., National Hydrology Research Institute, Saskatoon, Saskatchewan.

Parry, V., P. Nieneow, D. Mair, J. Scott, B. Hubbard, K. Steffen, and D. Wingham (2007), Investigation of meltwater refreezing and density variations in the snowpack and firn within the percolation zone of the Greenland ice sheet, *Ann. Glaciol.*, *46*, 61–68, doi:10.3189/172756407782871332.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean. Trajectory shifts in the Arctic and Subarctic freshwater cycle, *Science*, *298*, 2171–2173.

Peterson, B. J., J. McClelland, R. Curry, R. M. Holmes, J. Walsh, and K. Agard (2006), Trajectory shifts in the Arctic and Subarctic freshwater cycle. *Science*, *313*(5790), 1061–1066, doi:10.1126/science.1122593.

Pfeffer, W. T., J. T. Harper, and S. O'Neel (2008), Kinematic constraints on glacier contributions to 21st-century sea-level rise, *Science*, *321*, 1340–1343, doi:10.1126/science.1159099.

Prowse, T. D., and P. O. Flegg (2000), The magnitude of river flow to the Arctic Ocean: Dependence on contributing area, *Hydrol. Processes 14* (16–17), 3185–3188.

Ramillien, G., S. Bouhours, A. Lombard, A. Cazenave, F. Flechtner, and R. Schmidt (2008), Land water storage contribution to sea level from GRACE geoid data over 2003–2006, *Global Planet. Change*, *60*, 381–392, doi:10.1016/j.gloplacha.2007.04.002.

Rawlins, M. A., B. M. Willmott, A. I. 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.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland Ice Sheet, *Science*, *311*, 986–990, doi: 10.1126/science.1121381.

Rignot, E., J. E. Box, E. Burgess, and E. Hanna (2008), Mass balance of the Greenland ice sheet from 1958 to 2007, *Geophys. Res. Lett.*, *35*, L20502, doi:10.1029/2008GL035417.

Smith, L. C., T M Pavelsky, G. M. MacDonald, A. I. Shiklomanov, and R. B. Lammers (2007), Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle, *J. Geophys. Res.*, *112*, G04S47, doi:10.1029/2006JG000327.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Trabant, D. C., and L. R. Mayo (1984), Estimation and effects of internal accumulation on 5 glaciers in Alaska, *Ann. Glaciol.*, *6*, 113–117.

van de Wal, R. S. W., W. Boot, M. R. van den Broeke, C. J. P. P. Smeets, C. H. Reijmer, J. J. A. Donker, and J. Oerlemans (2008), Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet, *Science*, *321*, 111–113, doi:10.1126/science.1158540.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen (2002), Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, *297*, 218–222.

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