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Recent large increases in freshwater fluxes from Greenland into the North Atlantic

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[1] Freshwater (FW) fluxes from river runoff and precipitation minus evaporation for the pan Arctic seas are relatively well documented and prescribed in ocean GCMs. Fluxes from Greenland on the other hand are generally ignored altogether, despite their potential impacts on ocean circulation and marine biology. Here, we present a reconstruction of the spatially distributed FW flux from Greenland for 1958–2010. We find a modest increase into the Arctic Ocean during this period. Fluxes into the Irminger Basin, however, have increased by fifty percent (6.3 ± 0.5 km^3 yr^{-2}) in less than twenty years. This greatly exceeds previous estimates. For the ice sheet as a whole the rate of increase since 1992 is 16.9 ± 1.8 km^3 yr^{-2}. The cumulative FW anomaly since 1995 is 3200 ± 358 km^3, which is about a third of the magnitude of the Great Salinity Anomaly (GSA) of the 1970s. If this trend continues into the future, the anomaly will exceed that of the GSA by about 2025. **Citation:** Bamber, J., M. van den Broeke, J. Ettema, J. Lenaerts, and E. Rignot (2012), Recent large increases in freshwater fluxes from Greenland into the North Atlantic, *Geophys. Res. Lett.*, *39*, L19501, doi:10.1029/2012GL052552.

1. Introduction

[2] Freshwater (FW) fluxes from Greenland into the North Atlantic can affect the strength of the Atlantic meridional overturning circulation (AMOC) [*Fichefet et al.*, 2003; *Swingedouw et al.*, 2006], throughflow [*Marsh et al.*, 2010], estuarine circulation [*Straneo et al.*, 2011], glacier dynamics [*Seale et al.*, 2011], the marine ecosystem [*Rysgaard et al.*, 2003] and atmospheric temperatures [*Smith and Gregory*, 2009]. Changes in the FW budget of the region are, therefore, of wide scientific importance [*Curry and Mauritzen*, 2005; *Peterson et al.*, 2006] and a considerable body of literature exists on documenting the fluxes from rivers and precipitation minus evaporation (P-E) [*Aagaard and Carmack*, 1989; *Newton et al.*, 2008; *Peterson et al.*, 2002; *Schlosser et al.*, 2002]. A major omission from these studies, and from ocean circulation experiments, is a reliable estimate for the FW flux from Greenland and its evolution over time. Here, we present the first comprehensive assessment of the regional distribution of Greenland FW flux from a combination of surface runoff, R, and solid ice discharge, D, across the grounding line derived from a combination of climate modeling, and satellite and terrestrial data.

2. Methods

[3] Runoff was derived from a fifty three year reconstruction (1958–2010) of the surface mass balance (SMB) of the Greenland Ice Sheet and surrounding, non-glaciated tundra, using a high-resolution regional climate model, RACMO2 [*Ettema et al.*, 2009]. The atmospheric part of the model was forced at the lateral boundaries and the sea surface by ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis data (ERA-Interim) covering the period 1989–2009. For the period 1958–1988, the model was forced by ERA-40 reanalysis data. In RACMO2, 2 m temperature averaged over Greenland differs by only ~0.1 C between ERA40 and ERA-Interim forced runs for the overlapping time period (1989–2002), and runoff is also almost identical at 264 ± 63 Gt yr^{-1} (ERA40) and 268 ± 61 Gt yr^{-1} (ERA-Interim). RACMO2 was interactively coupled to a SMB model for the ice sheet and a land-surface scheme for the non-glaciated tundra to estimate total runoff. The coupled model was not tuned or calibrated with observations and shows excellent agreement with *in-situ* SMB data [N = 265, correlation coefficient 0.95] [*Ettema et al.*, 2009]. There are, however, few in-situ observations of runoff to validate the model with. A set of measurements along the K-transect in West Greenland [*Ettema et al.*, 2010, 2009] were combined with a comparison of melt area estimates from passive microwave data [*Fettweis et al.*, 2011] to produce an estimated uncertainty in ice sheet runoff of 20%. In our simulation there was little change in water storage/depletion so the tundra runoff is dependent primarily on precipitation, which has been compared with coastal meteorological station data [*Ettema et al.*, 2009] and has an estimated uncertainty of 10% for runoff from this analysis.

[4] D was derived from regional estimates of ice motion for thirty seven drainage basins covering about 95% of the ice sheet and incorporating annual sampling from 1992 onward but with intermittent coverage in time and space prior to 1992. It is calculated from surface velocity measurements multiplied by the ice thickness across some flux gate. For the purposes of this study the relevant flux gate is the grounding line: i.e., the point at which the ice enters the ocean. The velocity and ice thickness measurements were, however, obtained for gates a few kilometers upstream of the

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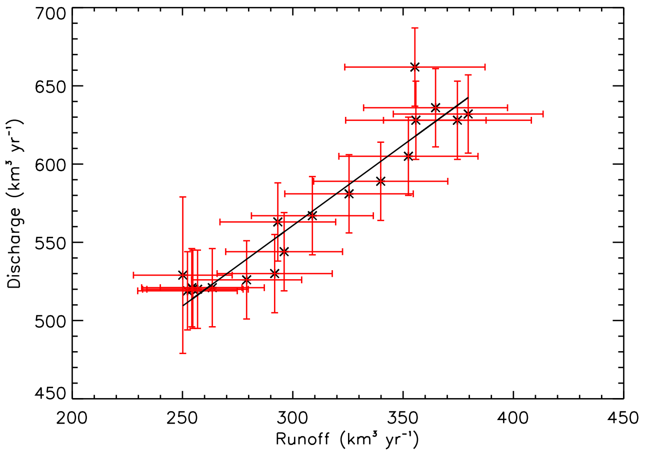

Figure 1. Plot of five-year averages of ice sheet runoff, R, against measured annual values of discharge covering the years 1958, 1964, 1992–2010. Error bars are 1 sigma. The least squares linear fit shown by the solid line is $D = 1.03 \times (\bar{R}_5)$, where $(\bar{R}_5) + 252.0$, where is the runoff averaged over the year of the discharge observation and preceding four years.

grounding line. As a consequence, it is necessary to include a SMB correction (on average about 8% of the discharge) for the area between the gate and the grounding line [*Rignot and Kanagaratnam*, 2006]. In this study we used the same SMB reconstructions that were used to determine runoff.

[5] A correlation between 3-year average SMB and D has been used in a previous study to interpolate the discharge estimates for 1964–1996 [*Rignot et al.*, 2008]. Here, we adopt an approach that builds on this, but with two important improvements. First, we have roughly twice the number of observations of D, with continuous sampling for 1992–2010. Second, we correlate runoff over the previous four years and current year ($\bar{R}_5$) with discharge for that year ($R^2 = 0.95$, gradient = 1.0) rather than correlating with SMB (Figure 1). The relationship is significant at the 95% confidence level. This is an empirical approach that is aimed at determining the long-term trends in D and, by its nature, cannot capture short-term variability, i.e., less than a few years. At the whole ice sheet scale, our results indicate a relatively stable ice sheet until the 1990s. An extensive analysis of ice front positions supports this conclusion, indicating a stable ice sheet from the 1950s until at least the mid 1980s [*Howat and Eddy*, 2011]. The uncertainty in measured estimates of D for 1992 onward is ±25 km^3 w.e. (±∼6%) and ±50 km^3 w.e. for earlier years [*Rignot et al.*, 2008].

[6] The mass balance, MB, of the ice sheet is:

$$MB = SMB - D, \text{where } SMB = Acc - R \text{ and } FW\,flux = R + D \quad (1)$$

where Acc is the accumulation. Thus the SMB, and hence MB, can vary due to changes in Acc that do not directly affect the FW flux (R + D). It should be noted, therefore, that trends in FW flux may not be the same as trends in MB because of the influence of changes in precipitation that directly impact the latter but only indirectly influence the former.

[7] SMB-D (i.e., MB) was compared with satellite gravity-derived estimates of mass balance for the period 2003–2008 [*van den Broeke et al.*, 2009] and more recently for the period 1992–2010 [*Rignot et al.*, 2011], which provides an independent test of our SMB and D estimates used here. Excellent agreement was found in both the phase and amplitude of the annual cycle when compared to the gravity-derived values [*van den Broeke et al.*, 2009]. An additional conclusion from this comparison was that the sub-annual variation in D is small compared with the amplitude of the total seasonal mass balance cycle, confirming previous results obtained for a subset of marine-terminating Greenland glaciers [*Rignot and Kanagaratnam*, 2006], and supporting the approximation made in this study that, integrated over the ice sheet, D has limited seasonality. It is important to note, here, that the large seasonal fluctuations in velocity observed for a number of land-terminating glaciers in Greenland [*Joughin et al.*, 2008] has no impact on D because they are not in direct contact with the ocean.

3. Results

[8] We examine, first, the time-evolving FW flux for the whole ice sheet (Figure 2). In the discussion that follows we compare recent trends to a "reference period", 1961–1990, where SMB shows no trend [*van den Broeke et al.*, 2009] and the ice sheet is relatively stable [*Howat and Eddy*, 2011]. We compare this with the most recent nineteen years, where we have annual sampling in D, and where the trend in R is a clear response to atmospheric warming in Greenland [*Hanna et al.*, 2012]. D and R have mean values of 497 ± 50 and 416 ± 57 $km^3\ yr^{-1}$ water equivalent, respectively, for the reference period (Figure 2). Runoff is split between an ice sheet and tundra contribution of 251 ± 50 and 165 ±17 $km^3\ yr^{-1}$, respectively. Based on the processes controlling ice dynamics we would not expect, and do not observe (for 1992–2010), significant annual

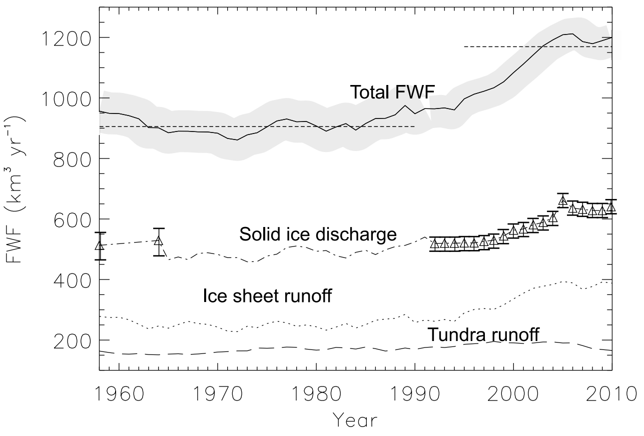

Figure 2. Ice sheet and tundra runoff, discharge and total freshwater fluxes from Greenland for 1958–2010. The triangles indicate the dates where discharge data were available and the error bars are the 1-sigma uncertainty in discharge. Uncertainty in tundra and ice sheet runoff is 10 and 20%, respectively, as discussed in the text. The grey shading indicates the RMSE of the FW flux estimate based on the errors for each term as described in the text. The horizontal dashed lines for the total FWF indicate the mean values for 1961–1990 and 2000–2010. Runoff was smoothed with a 5 year running mean.

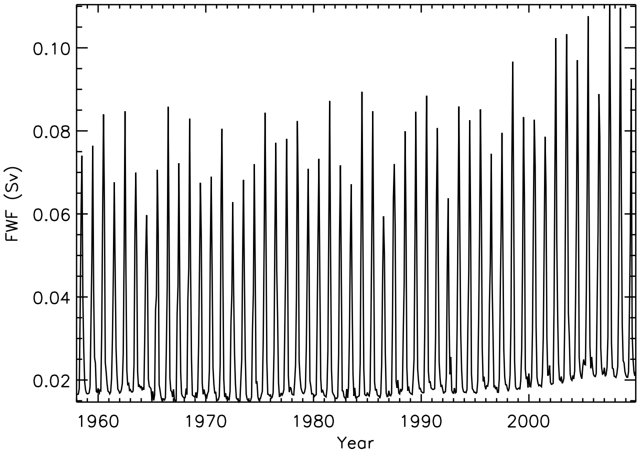

Figure 3. Total monthly FW fluxes for the whole of Greenland, comprising tundra and ice sheet runoff plus solid ice discharge. Units are Sverdrups, equivalent to 31,500 km^3 yr^{-1}.

fluctuations in D at the whole ice sheet scale, although, locally, multi-annual changes have been noted for some outlet glaciers [*Howat et al.*, 2007]. R, however, displays relatively large inter-annual variability (17%) and a strong seasonal cycle (Figure 3). This component of the FW flux peaks in summer with a maximum that is typically five to eight times larger than the annual mean. Thus, seasonally, the total FW flux since 2002, has exceeded 0.1 Sv for about a month a year on five occasions (Figure 3). From the mid 1990s both R and D have increased (Figure 2), their sum reaching values that are twice the generally quoted estimate of 0.02 Sv (630 km^3 yr^{-1}) [*Dickson et al.*, 2007; *Dyurgerov et al.*, 2010]. Even the most recent compilation substantially underestimates the total FW flux from Greenland (328 km^3 yr^{-1} for 1961–1992) and its rate of increase [*Dyurgerov et al.*, 2010]. This is partly due to the omission of tundra runoff but also to an underestimate in the acceleration in mass loss [*Rignot et al.*, 2011]. By 2003, the FW flux had exceeded 1200 km^3 yr^{-1}, an increase of 39% above the reference period. The rate of increase since 1992 is 16.9 ± 1.7 km^3 yr^{-2}. The changes in D and R are, however, not uniformly distributed across the island. The FW flux anomalies, as a consequence, affect particular regions of the Arctic Ocean and Subpolar North Atlantic (SNA) differently.

4. Discussion and Conclusions

[9] To examine the regional pattern of fluxes and their temporal evolution we grouped the original ice sheet drainage basins into larger oceanographic units (Figure 4). Five regions were defined based on the major ice sheet basins and their connection to different water masses and circulation [*Curry and Mauritzen*, 2005]. Moving clockwise from the northern limit they are the Arctic Ocean (AO), Nordic Seas (NS), Irminger Sea (IS), Labrador Sea (LS) and Baffin Bay (BB). The time series of cumulative FW flux anomaly for each of these regions is shown in Figure 5. The AO and NS show a modest cumulative increase but with the lowest absolute fluxes overall (Figure S1 in the auxiliary material).[1]

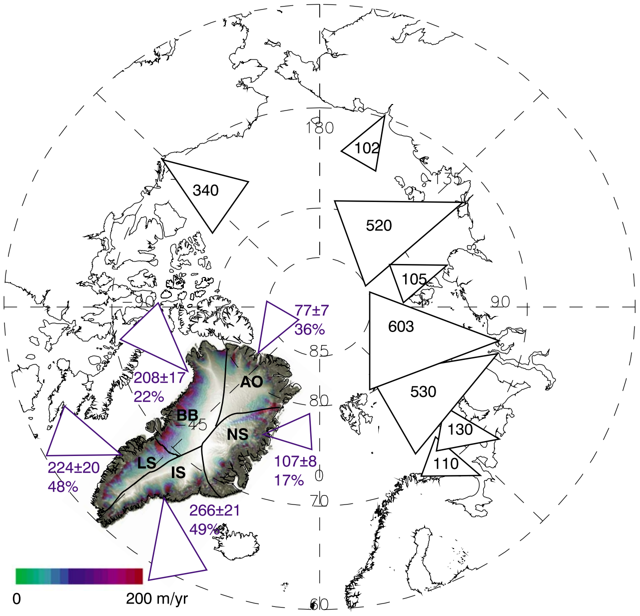

Figure 4. Map showing the scaled magnitude of FW flux (the area of each triangle is proportional to the flux) for the five oceanographic units described in the text and the eight largest rivers into the Arctic Ocean [after *Aagaard and Carmack*, 1989]. The numbers indicate the mean FW flux in km^3 yr^{-1} for the reference period 1961–1990 for each region and the percentages refer to the relative increase in flux for the period 1992–2010, based on a linear trend. Greenland is shown with surface topography, (grey shading) and steady-state ice velocities (colours) to indicate the location of outlet glaciers. The solid lines delineate the five drainage basins discussed in the text. AO = Arctic Ocean, NS = Nordic Seas, IS = Irminger Sea, LS = Labrador Sea, BB = Baffin Bay.

The largest changes have occurred in two disparate regions. The cumulative anomaly into the IS exceeded 1500 ± 154 km^3 by 2010 with a 49% absolute increase (Figures 4 and 5). The other region that has experienced a large absolute (700 ± 71 km^3) and relative increase (49%) in flux is the LS. The cumulative freshwater anomaly since 1995 for the whole of Greenland, which exceeds 3200 ± 358 km^3 in

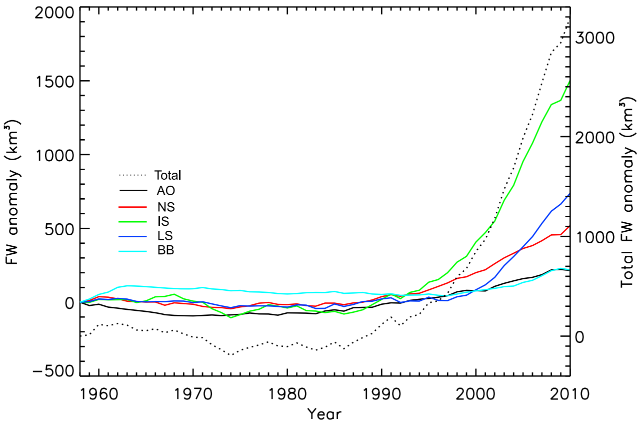

Figure 5. Cumulative FW anomalies for each region defined in Figure 4 and for the whole ice sheet (dashed line and right hand y-axis).

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL052552.

15 years, is the same order of magnitude to the FW contribution to the Great Salinity Anomaly (GSA) of the 1970s (10,000 km^3) [*Curry and Mauritzen*, 2005; *Dickson et al.*, 1988]. Notably, the trend for Greenland has been accelerating since the 1990s [*Rignot et al.*, 2011]. If this trend continues into the future, then the FW anomaly will exceed that of the GSA by 2025. Modeling studies indicate a steady decline in the 20th Century (continuing into the 21st) ice export through the Fram Strait [*Holland et al.*, 2006] while FW fluxes from Greenland are predicted to continue to increase [*Fettweis et al.*, 2008]. Thus, for the Irminger Basin, the role of Greenland FW fluxes is likely to become increasingly important.

[10] In addition to the impacts on the physical properties of the ocean, glacial runoff is an important source of nutrients [*Hood et al.*, 2009]. The large increase in FW flux into the IS and LS will, therefore, impact primary productivity both locally [*Rysgaard et al.*, 2003] and regionally [*Schofield et al.*, 2010; *Statham et al.*, 2008]. We conclude that studies must incorporate FW fluxes from Greenland and, in particular, their recent, and predicted, trends, if they want to understand, reproduce, and project, the impacts of climate change on the physical and biological properties of the pan-Arctic seas.

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