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Interactive comment on "Increasing runoff from the Greenland Ice Sheet at Kangerlussuaq (Søndre Strømfjord) in a 30-year perspective, 1979–2008" *by* S. H. Mernild et al.

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Runoff and mass-balance simulations from the Greenland Ice Sheet at Kangerlussuaq (Søndre Strømfjord) in a 30-year perspective, 1979–2008

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Abstract This study provides insights into surface mass-balance (SMB) and runoff exiting the Watson River drainage basin, Kangerlussuaq, West Greenland during a 30 year period (1978/79–2007/08) when the climate experienced increasing temperatures and precipitation. The 30-year simulations quantify the terrestrial freshwater output from part of the Greenland Ice Sheet (GrIS) and the land between the GrIS and the ocean, in the context of global warming and increasing GrIS surface melt. We used a snow-evolution modeling system (SnowModel) to simulate the winter accumulation and summer ablation processes, including runoff and SMB, of the ice sheet: indicating that the simulated equilibrium line altitude (ELA) was in accordance with independent observations. To a large extent, the SMB fluctuations could be explained by changes in net precipitation (precipitation minus evaporation and sublimation), with 8 out of 30 years having negative SMB, mainly because of relatively low annual net precipitation. The overall trend in net precipitation and runoff increased significantly, while SMB increased insignificantly throughout the simulation period, leading to enhanced precipitation of 0.59 km3 w.eq. (or ~60%), runoff of 0.43 km3 w.eq. (or ~55%), and SMB of 0.16 km3 w.eq. (or ~85%). Runoff rose on average from 0.80 km3 w.eq. in 1978/79 to 1.23 km3 w.eq. in 2007/08. The GrIS satellite-derived melt-extent increased significantly, and the melting intensification occurred simultaneously with the increase in local Kangerlussuaq runoff, indicating that satellite data can be used as a proxy (r2 = 0.64) for runoff from the Kangerlussuaq drainage area.

1 Introduction Snow, glacier ice, and frozen ground influence runoff processes throughout the Arctic. Significant responses in the structure and function of Arctic landscapes are likely, therefore, to occur in a warming climate (McNamara and Kane 2009). The Greenland Ice Sheet (GrIS) – the largest terrestrial permanent ice- and snow-covered area in the Northern Hemisphere – is sensitive to changes in the climate. Observational and model-based studies of the GrIS have provided intriguing insights into a system-

wide response to climatic change and the effects of a warmer and wetter climate on cryospheric and hydrologic processes. The response has been manifested by an increasing surface melt extent, peripheral thinning, accelerating mass loss – especially in northwest Greenland, and increasing freshwater runoff (e.g., Krabill et al., 2000, 2004; Janssens and Huybrechts 2000; Johannessen et al., 2005; Fettweis, 2007; Hanna et al., 2009; Richardson et al., 2009; Khan et al. 2010), indicating that mass loss of the GrIS may be responsible for nearly 25% of observed global sea rise in the past 13 years (Mernild et al., 2009). An important component of an ice sheet's surface mass balance is meltwater runoff, yet there are few high-resolution freshwater runoff observations at the periphery of the GrIS (e.g., Hag et al., 2002; Hasholt and Mernild, 2009). A time series of river discharge from Kangerlussuaq (Søndre Strømfjord), West Greenland, has been recorded since 2007 and is of considerable importance to quantifying runoff from the ice sheet. These observations provide insight into the onset, duration, variation, and intensity of runoff, and the changes in intraannual and interannual hydrological response. It is essential to assess the impact of climate change on the GrIS, since the temperature rise in the northern latitudes is more pronounced than the global average; the observed increase is almost twice the global average rate of the past 100 years (IPCC 2007). Thus, the present state of the GrIS runoff should be established to detect warning signs indicative of the ice sheet's future response. Projected climate scenarios suggest that the runoff will increase in Arctic (ACIA 2005). This study improves the quantitative understanding of freshwater runoff from the Watson River drainage basin, near Kangerlussuaq, West Greenland. In this study we applied a surface modeling system called SnowModel (Liston and Elder 2006; Liston et al., 2007; Mernild et al., 2010b; Mernild and Liston, 2010) to the Kangerlussuaq region for the 30-year period from 1978/79 through 2007/08 to illustrate the observed climate-driven fluctuations in the water balance components. Our objectives were related to the changes in climate: 1) to simulate the variations and trends in the surface-water-balance components: precipitation, changes in storage, and freshwater runoff for the Kangerlussuaq catchment, and address whether Kangerlussuaq runoff can be used as a proxy for the whole GrIS

runoff; 2) to estimate the percentage of catchment runoff explained by GrIS runoff; and 3) to compare satellite-derived GrIS melt-extent changes with the local Kangerlussuaq simulated runoff patterns to illustrate the link between surface melt and freshwater runoff, and whether satellite data are useful proxies of runoff from the Kangerlussuaq drainage area. This paper differs from previous Kangerlussuaq runoff studies (2007–2008) by Mernild and Hasholt (2009) and Mernild et al. (2010a), and previous runoff studies covering the whole GrIS (Mernild et al. 2008, 2009). Here, we provide knowledge on local scale for Kangerlussuaq about net precipitation, SMB, and runoff and its variations for the entire period 1978–2008 based on observed climate-driven fluctuations, instead of only: 1) being focused on the hourly and daily observed and simulated Kangerlussuaq runoff for the years 2007 and 2008 (Mernild and Hasholt, 2009; Mernild et al., 2010a); or 2) being focused on the overall water balance conditions for the entire GrIS (Mernild et al. 2008, 2009).

2 Study area 2.1 Physical settings, meteorological stations, and climate The Kangerlussuaq drainage area (6130 km2) is located on the west coast of Greenland (67°N latitude; 50°W longitude) (Fig. 1a). The river outlet is located about 22–35 km downstream from the GrIS terminus, near Kangerlussuaq (Søndre Strømfjord), a town at the head of the Kangerlussuaq fjord. The outlet location is easily accessible and one of the most tractable for observing GrIS runoff because of well-defined, stable bedrock cross sections; braided channels with unstable banks characterize most other river outlets in Greenland, making accurate runoff monitoring almost impossible. The upper part of the catchment area is dominated by the GrIS, and by bare bedrock, sparse vegetation cover, and river valleys in the lower parts. The Kangerlussuaq region is considered Low Arctic according to Born and Böcher (2001). The SnowModel-simulated mean annual air temperature for the catchment (Fig. 1b) (1978/79–2007/08) is −10.9°C. Mean annual relative humidity is 64%, and mean annual wind speed is 5.3 m s−1. The corrected mean total annual precipitation (TAP) is 246 mm w.eq. y−1 (1978/79–2007/08) (corrected after Allerup et al., 1998, 2000). The mean (1990–2003) equilibrium line altitude (ELA; defined as the elevation on the GrIS where the net mass balance is zero)

in the region is ~1530 m a.s.l., located near Station S9 (van de Wal et al., 2005; van den Broeke et al., 2008c).

3 Methods 3.1 SnowModel description SnowModel (Liston and Elder, 2006) is a spatially distributed snow-evolution, ice melt, and runoff modeling system designed for application in landscapes (e.g., Arctic and Antarctica), climates, and conditions where snow and ice play an important role in hydrological cycling (Mernild et al., 2006; Mernild and Liston, 2010). SnowModel is an aggregation of five submodels: MicroMet, EnBal, SnowPack, SnowTran-3D, and SnowAssim. MicroMet defines meteorological forcing conditions; EnBal calculates surface energy exchanges and melt; SnowPack simulates snow depth, water-equivalent evolution, and runoff; SnowTran-3D accounts for snow redistribution by wind; and SnowAssim assimilates available snow measurements to create simulated snow distributions that closely match observed distributions (for a detailed description of SnowModel, its submodels and modifications see Liston et al. (2008) and Mernild and Liston (2010) and references herein).

3.2 SnowModel input To solve the SnowModel equations, data were obtained from four meteorological stations within the simulation domain, with three of them located on the GrIS from the K-transect and one at the airport of the town Kangerlussuaq (Station Kangerlussuaq, hereafter referred to as Station K; Fig. 1b, Table 1). Station K (67°10âĂšN, 50°42âĂšW; 50 m a.s.l.; a Danish Meteorological Institute (DMI) WMO meteorological station) is representative of the proglacial area. This station was moved in 2004 to its current location. No air temperature correction was made for the current study because the new station elevation of 50 m a.s.l. is the same as the old site (for further information see Table 1). On the GrIS, three automatic weather stations are operated by Utrecht University. Stations S5 (67°06âĂšN, 50°07âĂšW; 490 m a.s.l.), S6 (67°05âĂšN, 49°23âĂšW; 1020 m a.s.l.), and S9 (67°03âĂšN, 48°14âĂšW; 1520 m a.s.l.) are all part of the K-transect, located on the ice sheet and representative of GrIS conditions (for further information about the K-transect stations see, e.g., van de Wal et al., 2005; van den Broeke et al., 2008a, b, c). The simulations span the 30-

year period 1 September 1978 through 31 August 2008, approximately following the annual GrIS mass-balance year and coinciding with the period of available passive microwave satellite-derived GrIS melt extent data. The simulations were performed on a daily time step. For 2003/04 through 2006/07, meteorological input data from Stations K, S5, S6, and S9 were used, and for the period before (1978/79 through 2002/03) and after (2007/08) that time, only data from Station K were used. Since meteorological data only were available from Stations S5, S6, and S9 (representative of GrIS conditions) for some of the simulations, the runoff was re-simulated based on Station K input data only for the same period. This simulation overestimated the 2003/04 through 2006/07 cumulative runoff by ~210 through ~240%, averaging ~230%, due, for example, to the higher average temperature conditions in the proglacial landscape (in tundra), than on the GrIS. Station K experienced quite different temperatures compared to the GrIS: The summer days can be warm, since the proglacial area and the tundra is relatively dark and dry. In contrast, winters at Station K are colder than over the GrIS, because the absence of persistent katabatic winds allows formation of strong temperature inversions in the valleys. If not corrected, the use of meteorological station data from the proglacial area alone will overestimate the GrIS runoff during summer season. Therefore, this average ~230% overestimation was used in order to adjust the 1978/79 through 2002/03 and 2007/08 simulated runoff, which then agrees to within ~10% to the observed 2007 and 2008 cumulative runoff. Mean monthly lapse rates (September 2003 through August 2007) were defined for the model simulations based on air temperature observations along a transect drawn between Stations S5, S6, and S9. Precipitation at the DMI meteorological station (Station K; Fig. 1b, Table 1) was defined by correcting Helman–Nipher shielded gauge observations following Allerup et al. (1998, 2000). Greenland topographic data for model simulations were provided by Bamber et al. (2001), and corrections were determined by Scambos and Haran (2002). The digital elevation model was aggregated to a 500-m grid-cell increment and clipped to yield a 750-by-580-km simulation domain (435000 km2) (Fig. 1b). The GrIS terminus was confirmed or estimated by using satellite images (Google Earth, Image

2009). A variable snow albedo was used (Mernild et al., 2010b). User-defined constants for SnowModel are shown in Table 2 (for parameter definitions, see Liston and Sturm, 1998, 2002).

3.3 SnowModel calibration, verification, and uncertainty To assess the general performance of SnowModel simulated values were tested against independent observations. SnowModel/MicroMet-distributed meteorological data: air temperature, wind speed, precipitation, and relative humidity have been compared against independent Greenland meteorological station data both on and outside the GrIS, indicating respectable representations of meteorological conditions: Air temperature (87–99% variance), wind speed (55–98%), precipitation (49–98%), and relative humidity (48–96%) (for further information, see Mernild et al., 2008; Mernild and Liston, 2010). SnowModel accumulation and ablation routines were tested both qualitatively and quantitatively using independent in situ field observations on snow pit depths; glacier winter, summer, and net mass-balances; depletion curves; photographic time lapses; and satellite images from in and outside the GrIS (for an overview of the different tests and maximum differences, see Table 3 in Mernild et al. 2009 and Mernild and Liston 2010): A comparison performed between simulated and observed values indicated good agreement, and an approximately 10–25% maximum difference between modeled and observed observations based on statistical analysis from previous SnowModel studies. Therefore, it is expected that the results – the accumulation and ablation processes, including runoff estimates, presented in this study are affected with the same level of uncertainty of 10–25%, as shown in previous studies. To assess the winter and summer model performance for this Kangerlussuaq study, the end-of-winter (31 May; recognized as the end of the accumulation period) simulated snow depth was compared with Station S5, S6, and S9 observed snow depths, and the simulated cumulative summer (June through August) runoff was compared with observed catchment outlet runoff entering directly into Kangerlussuaq Fjord. The snow depths were measured at 31 May (Table 3), and used to verify and adjust the SnowModel-simulated snow depth. Using Station K precipitation, the simulated snow depth was on average overestimated by

up to $\sim$50% (400 mm w.eq.) (2003/04–2006/07) for Station S9. Therefore, the iterative precipitation-adjustment and convergence scheme following Liston and Hiemstra (2008) was implemented, yielding a simulated Station S9 snow depth on 31 May that was within 1% of the observed snow depth (Table 3). As a test, Station S5 and S6 simulated end-of-winter snow depths were within $\sim$10% of the observed end-of-winter snow depths. Catchment outlet runoff was observed for the 2007 and 2008 runoff seasons (Mernild and Hasholt, 2009), and both years were used for verification. The observed runoff had an accuracy of 10–15% (Mernild and Hasholt, 2009). Furthermore, independent glacier net mass-balance observations along the K-transect were used for verification of the simulated net mass-balance (van de Wal et al. (2005) (for further information see Chapter 4; Fig. 2). Simulated ELA was further validated against independent ELA studies from Zwally and Giovinetto (2001) and Fettweis (2007). It is important to keep in mind the limitations of these SnowModel results since uncertainties are associated with model inputs and unrepresented or poorly-represented processes in SnowModel. For example, glacier dynamic and sliding routines for simulating changes in GrIS area, size, and surface elevation are not yet represented within the modeling system. In addition, runoff from geothermal heating/melting was not included in the calculations. It is also noted that changes in GrIS storage based on supraglacial, englacial, subglacial, and proglacial storage, internal meltwater routing, and evolution of the internal runoff drainage system are not calculated in SnowModel; these neglected processes are unlikely to be significant unless there are long term, secular changes in glacier geometry and drainage system structure.

3.4 Satellite images Satellite microwave data were used to detect surface melt at large spatial scales for the GrIS. The GrIS snowmelt extent was mapped daily using passive microwave satellite observations (25-km grid-cell increment). The satellite observations are able to discriminate wet from dry snow. The criterion for melt is 1% mean liquid water content by volume in the top meter of snow (Abdalati and Steffen, 1997). The end-of-summer maximum observed spatial surface melt distribution on the GrIS was compared with Kangerlussuaq runoff.

4 Results and discussion Throughout the year, different surface processes such as snow accumulation, snow redistribution and sublimation, surface evaporation, and surface melt affect the GrIS SMB and the high-latitude water balance, including runoff. Sublimation may play an important role in the annual high-latitude hydrological cycle. Previous GrIS studies (e.g., Box and Steffen, 2001; Mernild et al., 2008) have shown that as much as 17–23% of the annual precipitation was returned to the atmosphere by sublimation, and studies in Arctic North America (e.g., Liston and Sturm, 1998, 2004; Essery et al., 1999; and Pomeroy and Essery, 1999) indicated that 5–50% of the annual solid precipitation was returned. For the Kangerlussuaq drainage area (Fig. 1) (1978/79–2007/08), modeled annual sublimation, including blowing-snow sublimation, averaged 0.33 ($\pm$0.08) km3 y$-$1, or $\sim$17% of the annual precipitation input. Simulated evaporation, however, averaged 0.31 ($\pm$0.07) km3 y$-$1, indicating that total loss from sublimation and evaporation was 0.64 ($\pm$0.16) km3 y$-$1, which equaled $\sim$33% of the annual precipitation input. Loss from transpiration from the proglacial area between the GrIS terminus and Kangerlussuaq Fjord was not taken into account for the Kangerlussuaq simulations since vegetation in this area is so limited. Figure 2a illustrates the simulated GrIS SMB variations with elevation (340 to 1,800 m a.s.l.) for the Kangerlussuaq drainage area for the years 1990/91 through 2002/03 (the same period as published in van de Wal et al. (2005)). Net accumulation occurred over the GrIS interior (above the ELA), while net surface ablation dominated the terminus/low-lying parts of the GrIS (below the ELA). The modeled ELA zone fluctuated from 1,370 to 1,780 m a.s.l., which was in accordance with observations from van de Wal et al. (2005). The ELA zone indicated that Station S9 was positioned within the boundaries. The average simulated ELA located at $\sim$1,560 m a.s.l. was significant (97.5% quantile) with the observed mean ELA at $\sim$1,530 m. a.s.l. by van de Wal et al. (2005) (Fig. 2b). The location of the simulated ELA was also found to be consistent with the ELA parameterization of Zwally and Giovinetto (2001) and Fettweis (2007). The observed SMB gradient was 3.7$\times$10-3 m m-1 in the ablation area, and was comparable to the simulated gradient of 3.3$\times$10-3 m m-1, and to the gradient at Jakobshavn, West Greenland, of 3.5$\times$10-3 m m-1

(Mernild et al. 2010b). At the GrIS margin the average SMB loss was $\sim$4.0 m w.eq y-1, with maximum annual values up to $\sim$4.8 m w.eq. (Fig. 2a and 2b). Figure 3a presents water balance components for the Kangerlussuaq drainage area from 1978/79 through 2007/08. Statistically significant relationships exist between net precipitation and SMB, and runoff and SMB: The interannual variability in net precipitation and runoff caused sizeable SMB fluctuations with correlations of $r2 = 0.51$, $p < 0.01$, and $r2 = 0.22$, $p < 0.01$, respectively (where r2 is the explained variance; p is the level of significance). Surface mass-balance fluctuations were largely tied to changes in net precipitation processes, and less to summer air temperatures. Throughout the simulation period, SMB varied from $-$0.39 (1979/80) to 0.97 km3 w.eq. (1982/83), averaging 0.26 ($\pm$0.34) km3 w.eq. y$-$1. The SMB values were consistent with previous Kangerlussuaq SMB simulations by Mernild et al. (2009), based on simulations for the entire ice sheet (without using K-transect observations as forcing fields), and in line with results provided by the MAR (ModeÌĂle Atmosphérique Régionale) model (Gallée and Schayes 1994), showing that SMB variations in the Kangerlussuaq area explained the SMB variability of the whole GrIS with a correlation of near 0.9 (Fettweis 2007). In 8 out of 30 simulation years, the SMB was negative (Fig. 3a), mainly because of relatively low net precipitation. For the 1978/79–2007/08 simulations, 1979/80, 1989/90, 1984/85, and 1983/84 were the first, second, third, and fourth lowest-precipitation years, respectively, and 1979/80, 1989/90, 1998/99, and 1984/85 were the first, second, third, and fourth lowest-SMB years, respectively. The year 1982/83 had the highest positive SMB of 0.97 km3 w.eq., because of relatively high net precipitation (1.60 km3 w.eq.) and low runoff (0.62 km3 w.eq.). For the years 1998/99 and 2006/07, however, the low SMB was based on high runoff values, where 2006/07 and 1998/99 had the first and second highest runoff, respectively (Table 4). For 2006/07, the runoff was 1.76 km3 w.eq.; approximately 75% higher than the average runoff for the period 1978/79 through 2007/08 (except for 2006/07) of 0.99 ($\pm$0.21) km3 w.eq. y$-$1. The overall trend in Fig. 3a illustrates a significant increase of both net precipitation and runoff during the 30-year time period, with increases in precipitation of 0.59 km3 w.eq. (or $\sim$60%) (r2 =0.33, p

< 0.01) and in runoff of 0.43 km3 w.eq. (or ∼55%) (r2 = 0.31, p < 0.01). The runoff rose on average from 0.80 km3 w.eq. in 1978/79 to 1.23 km3 w.eq. in 2007/08. A rise in Kangerlussuaq runoff was also found in simulations of Mernild et al. (2009), based on consideration of the entire ice sheet. For the SMB, however, the increase indicated an insignificant trend (r2=0.02, p<0.10), leading to an enhanced average gain of mass of 0.16 km3 w.eq. (or ∼85%), largely due to changes in precipitation. Since storm tracks determine the distribution of precipitation across Greenland (e.g., Hansen et al., 2008), the average increase in precipitation in the Kangerlussuaq area was most likely due to changes of the passage of low pressure systems around Greenland. Figure 3b presents the simulated outlet runoff from the Kangerlussuaq drainage area from 1978/79 through 2007/08, subdivided between runoff originating from the GrIS (based on snow and ice melt, and liquid precipitation) and from the proglacial area outside the GrIS (based on snowmelt and liquid precipitation): to get the runoff contribution from the proglacier landscape, the GrIS runoff was subtracted from the overall catchment runoff. The percentage of catchment runoff explained by runoff from the GrIS varied from a maximum of 70% in 1979/80 to a minimum of 36% in 2004/05, averaging 51(±9)% (Fig. 2b), where 70% of the explained variance in catchment runoff was from GrIS runoff (and without the extreme 2006/07 value the explained variance was 58%) (Fig. 3c). Further, the variation in percentage of catchment runoff explained by the GrIS was significantly influenced by changes in SMB (r2 =0.65, p<0.01), showing that years with high percentage values correspond to years with negative SMB, and vice versa. Seasonal variation in runoff is illustrated in Figs. 4a and b, both for catchment runoff and GrIS runoff for the year, with the minimum (1991/92) and maximum (2006/07) cumulative runoff. During winter (September/October through May/June), no runoff events were simulated for the Kangerlussuaq drainage area for the period 1978/79 through 2007/08. For the year 2006/07, the first day of modeled runoff occurred at the end of May. Visual observations from 2006/07 and 2007/08 indicated that outlet runoff normally starts around mid/late April (Hasholt and Mernild, 2009), approximately 2–3 weeks before simulated runoff, and stops late September to mid-October,

which was in accordance with simulated values. In the early melt period (April and May), runoff was controlled mainly by snowmelt in the landscape and on the GrIS, whereas later in the season (mid-July and August) when the seasonal snow cover had largely melted, runoff was dominated by GrIS glacier-ice melt. When surface melting was defined by SnowModel, meltwater is assumed to be transported as “runoff” instantaneously when the surface consists of glacier ice. When snow cover was present, the SnowPack runoff routines take retention and internal refreezing into account when meltwater forms at the surface and penetrates the snowpack. These routines have an effect on the runoff lag time and the amount of runoff. If no retention/refreezing routines were included in SnowModel, the initial seasonal runoff would occur up to, e.g., 81 days before, and the Kangerlussuaq runoff would be overestimated by up to ∼65%. Surface-modeled water-balance components for the Kangerlussuaq drainage area were compared with an overall GrIS area surface study from 1995/96 through 2006/07 (Mernild et al., 2009). For Kangerlussuaq, the average simulated runoff of 1.02 (±0.25) km3 y−1, equals 2.5‰ of the average GrIS surface runoff of 397 (±62) km3 y−1. The Kangerlussuaq runoff trend, illustrated in Fig. 3a, is in accordance with the runoff trend for the GrIS; both indicating increasing runoff. The simulated variations in Kangerlussuaq runoff and the overall GrIS runoff (simulated based on 5-km grid-cell increment) were significant equal (r2=0.53; p<0.01), even though only 53% of the variations in Kangerlussuaq runoff were explained by variations in the GrIS runoff. Here, it should be kept in mind that the comparison only was based on an overlap of runoff for 12 years, therefore using Kangerlussuaq runoff as representative of the overall GrIS runoff should be done with caution. For the whole GrIS the trend in precipitation was almost zero, while GrIS SMB decreased, leading to enhanced average GrIS mass loss. The average GrIS SMB pattern was different from the local trends at Kangerlussuaq, West Greenland, probably because the characteristics of Greenland caused considerable contrast in its weather conditions. Local climatic trends often differ over short distances due to the complex coastal topography, elevation gradients, distance from the coast, marginal glaciers, and the presence of the GrIS, but also because of larger-scale climatic influences over Greenland related, for example, to the distance from the North Atlantic Oscillation (NAO) northern center of action near Island (e.g., Hanna and Cappelen (2003), Hurrell and Deser (2009)), and to the Atlantic Multidecadal Oscillation, AMO; e.g., Folland et al. (1986), Schlesinger and Ramankutty (1994), Kerr (2000)). In Fig. 5a, a time series of the satellite-derived GrIS total melt area is shown (data provided by CIRES, University of Colorado at Boulder), together with local Kangerlussuaq runoff from 1978/79 to 2007/08 to illustrate the correspondence between surface melt and freshwater runoff. For the simulation period, the GrIS melting area increased significantly ~60% on average (Richardson et al., 2009), where the year 2007 indicated record GrIS surface-melt extent according to observations (Mote 2007; Tedesco 2007; Richardson et al., 2009). The melting intensification occurred simultaneously with the increase in local Kangerlussuaq runoff, and for Kangerlussuaq, the runoff significantly increased by ~55% from 1978/79 through 2007/08 ($r2 = 0.30$, $p < 0.01$). Further, for the year 2006/07, record modeled Kangerlussuaq runoff of 1.76 km3 w.eq. occurred (Table 4). The variations in Kangerlussuaq runoff from 1978/79 through 2007/08 closely follow the overall variations in satellite-derived GrIS surface melt area (Fig. 5a) (however, the simulated runoff does not take into account year-to-year runoff variations due to all possible changes in GrIS freshwater storage), where 64% of the simulated runoff variation could be explained by satellite-derived melt area (Fig. 5b). The satellite-derived GrIS melt-extent can therefore be used as a proxy of runoff from the Kangerlussuaq drainage area, as stated for the entire GrIS by Fettweis et al. (2006), indicating that runoff was directly proportional to satellite-derived melt extent. Here, it should be kept in mind that the 30-year Kangerlussuaq runoff variations not only are driven by melting conditions, but also by winter snow accumulation. Studies by Hanna et al. (2008) and Mernild et al. (2009) stated, for the GrIS in general: retention and refreezing in the snow pack indicated that high runoff years were synchronous with low precipitation/accumulation years, since more melt water was retained in the thicker snowpack, reducing runoff; This effect is most pronounced above the GrIS ELA, where melt water does not infiltrate far into the snowpack because of the cold state of the snowpack. Observations from the Kangerlussuaq drainage by Sugden et al. (1985), Roberts (2005), and Mernild and Hasholt (2009), for example, indicated that sudden short-lived glacial outburst floods (jökulhlaups) occurred. Each year in 1983 and 1984, a short-lived jökulhlaup event was observed, and again in 2007 and 2008 based on water stored on the GrIS surface, internally, or in ice-dammed lakes. While SnowModel does not simulate sudden releases of internal GrIS water storage, such events certainly influence peak seasonal runoff, isolated and rapid discharge events, and river dynamics and their impact on e.g., transporting sediment and nutrients to the fjord, even though jökulhlaups and similar discharge occurrences likely only account for a small percentage of the cumulative runoff. Understanding water movement and the hydrologic response within and below the GrIS is intrinsically complex and not well understood. It involves the liquid phase (water) moving through the solid phase (ice) at the melting temperature while the ice is deformable, allowing englacial and subglacial conduits to change size and shape. Furthermore, efforts to model the links between the GrIS's mass balance, its dynamic processes, changes, internal drainage, runoff, and subglacial sliding and erosion, including the Kangerlussuaq drainage area, still suffer from uncertainties and limitations. These uncertainties and limitations are related partly to insufficient knowledge of englacial routing and basal conditions at the GrIS ice-bed interface, and the effect from a lubricated interface that causes basal ice to slide over its bed. How the increasing volume of surface meltwater, due to increasing melt content, affects the dynamics and the subglacial sliding processes are still unanswered questions at Kangerlussuaq.

5 Summary and conclusion Thirty years of SnowModel simulations of runoff from a sector of the GrIS – the Kangerlussuaq drainage area – were provided for the period 1978/79 through 2007/08, a period of climatic change to a warmer and wetter climate. This simulated time series yielded insights into present conditions on the ice sheet and the interannual variability of SMB and runoff. The simulations indicate fluctuations in SMB that were largely tied to changes in net precipitation, showing 8 out of 30 years had negative SMB mainly because of relatively low annual net precipitation. The

increasing Kangerlussuaq runoff was substantially correlated with the overall pattern of the satellite-derived GrIS surface melt area, illustrating a correspondence between surface melt conditions and runoff: GrIS satellite data can therefore be used as a proxy of runoff from the Kangerlussuaq drainage area.

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