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Increasing runoff from the Greenland Ice Sheet at Kangerlussuaq (Søndre Strømfjord) in a 30-year perspective, 1979–2008

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Abstract

This observation and modeling study provides insights into 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 surface mass balance (SMB), of the ice sheet. 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 km^3 w.eq. (or 60%), runoff of 0.43 km^3 w.eq. (or 54%), and SMB of 0.16 km^3 w.eq. (or 86%). Runoff rose on average from 0.80 km^3 w.eq. in 1978/79 to 1.23 km^3 w.eq. in 2007/08. The percentage of catchment outlet runoff explained by runoff from the GrIS decreased on average ~10%.

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, and 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), 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.

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., 2009) in different way. 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 climate-driven fluctuations, in stead of only: 1) being focusing on the hourly and daily observed and simulated Kangerlussuaq runoff for the years 2007 and 2008 (Mernild and Hasholt, 2009; Mernild et al., 2010a); and 2) being focusing on the overall water balance conditions for the entire GrIS (Mernild et al., 2009).

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 climate-driven fluctuations to the water balance components. Our objectives were due 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 area; 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.

2 Study area

2.1 Physical settings, meteorological stations, and climate

The Kangerlussuaq drainage area (6130 km^2) 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. 1) (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 (S5, S6, and S9) from the K-transect and one at the airport of the town Kangerlussuaq representative of the proglacial area (Station Kangerlussuaq, hereafter referred to as Station K) (Fig. 1c, Table 1). Station K (67°01′N, 50°42′ W; 50 m a.s.l.; a Danish Meteorological Institute (DMI) WMO meteorological station) is located at the airport of the town

Kangerlussuaq and 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 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°06′ N, 50°07′ W; 490 m a.s.l.), S6 (67°05′ N, 49°23′ W; 1020 m a.s.l.), and S9 (67°03′ N, 48°14′ W; 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 ∼230% in average, 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 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. This average ∼230% overestimation was used for adjusting the 1978/79 through 2002/03 and 2007/08 simulated runoff, which then compares within ∼10% of 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. 1c, 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 correction was 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 (435 000 km^2) (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 (49–87% variance) representations of meteorological conditions (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 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 (e.g., Mernild et al., 2006, 2008). A comparison performed between simulated and observed values indicates a 10–25% maximum difference between modeled and observed observations.

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 31 May, and used to verify and adjust the SnowModel-simulated snow depth. Using Station K precipitation, the simulated snow depth was on average overestimated up to ~50% (400 mm w.eq.) (2003/04–2006/07) for Station S9. Therefore, an iterative precipitation-adjustment and convergence scheme following Liston and Hiemstra (2008) was implemented which yielded a simulated Station S9 snow depth on 31 May that was within 1% of the observed snow depth. As a test, Station S5 and S6 simulated snow depths were within 13% 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). It is important to keep in mind the limitations of these SnowModel results since uncertainties are likely influenced by processes not yet represented within the modeling system; for example, glacier dynamic and sliding routines for simulating changes in GrIS area, size, and surface elevation. In addition, runoff from geothermal heating/melting was not included in the calculations. Moreover, 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, and 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 was 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 at the GrIS was compared with Kangerlussuaq runoff, since there is a link between surface melt, melting snow and ice, and runoff.

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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 surface mass balance (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. Blowing-snow sublimation rates are mainly dependent upon air temperature, humidity deficiency, wind speed, and particle-size distribution (e.g., Pomeroy and Gray 1995; Liston and Sturm 2002). For the Kangerlussuaq drainage area (Fig. 1) (1978/79–2007/08), modeled annual sublimation averaged 0.33 (±0.08) $km^3 y^{-1}$, or ~17% of the annual precipitation input. In the entire Kangerlussuaq simulation domain, sublimation played a lesser role in the surface moisture budget. Simulated evaporation, however, averaged 0.31 (±0.07) $km^3 y^{-1}$, indicating that total loss from sublimation and evaporation was 0.64 (±0.16) $km^3 y^{-1}$, which equalled ~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 presents water balance components for the Kangerlussuaq drainage area from 1978/79 through 2007/08. The SMB was governed by accumulation (precipitation) and by ablation (evaporation, sublimation, and runoff). Net accumulation occurred over the GrIS interior (above the ELA). The ELA was approximately located from 1640 m a.s.l. to the south to 600 m a.s.l. to the north of the GrIS (see e.g., Zwally and Giovinetto, 2001; Box et al., 2004), while net surface ablation dominates the terminus/low-lying parts of the GrIS. Statistically significant relationships exist between net precipitation and SMB, and runoff and SMB: The interannual variability in net precipitation and runoff causes sizeable SMB fluctuations with correlations of $R^2 = 0.51$, $p < 0.01$, and $R^2 = 0.22$, $p < 0.01$, respectively. 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 km^3 w.eq. (1982/83), averaging 0.26 (± 0.34) km^3 w.eq. y^{-1}. In 8 out of 30 simulation years, the SMB was negative (Fig. 2a), 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 km^3 w.eq., because of relatively high net precipitation (1.60 km^3 w.eq.) and low runoff (0.62 km^3 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 3). For 2006/07, the runoff was 1.76 km^3 w.eq.; approximately 75% higher than the average runoff for the period 1978/79 through 2007/08 (except for 2006/07) of 0.99 (± 0.21) km^3 w.eq. y^{-1}. The overall trend in Fig. 2a illustrates a significant increase of both net precipitation and runoff during the 30-year time period, leading to enhanced average precipitation of 0.59 km^3 w.eq. (or 60%) ($R^2 = 0.33$, $p < 0.01$) and runoff of 0.43 km^3 w.eq. (or 54%) ($R^2 = 0.31$, $p < 0.01$). The runoff rose on average from 0.80 km^3 w.eq. in 1978/79 to 1.23 km^3 w.eq. in 2007/08. For the SMB, however, the increase indicated an insignificant trend ($R^2 = 0.02$, $p < 0.10$), leading to an enhanced average gain of mass of 0.16 km^3 w.eq. (or 86%), 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 is most likely due to changes of the passage of low pressure systems around Greenland.

Figure 2b presents the simulated outlet runoff from the Kangerlussuaq drainage area from 1978/79 through 2007/08, subdivided between runoff originating from the GrIS and from the area outside the GrIS, based on precipitation and snowmelt. 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. 2c). Further, the variation in percentage of catchment runoff explained by the GrIS was significantly influenced by changes in SMB ($R^2 = 0.65$, $p < 0.01$), showing that years with high percentage values correspond to years with negative SMB and vice versa. The overall trend ($R^2 = 0.11$, $p < 0.05$, significant) for the period 1978/79 through 2007/08 indicated that the percentage of catchment runoff explained by the GrIS decreased on average ~10% from 55% (1978/79) to 45% (2007/08). This decrease means that the catchment runoff throughout the simulation period was influenced more by runoff from outside the GrIS – from liquid precipitation and snowmelt events – and less by runoff from the GrIS.

Seasonal variation in runoff is illustrated in Figs. 3a 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 where 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 run 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 melts at the

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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 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) $km^3 y^{-1}$, equals 2.5‰ of the average GrIS surface runoff of 397 (±62) $km^3 y^{-1}$. The Kangerlussuaq runoff trend, illustrated in Fig. 2a, is in accordance with the runoff trend for the GrIS; both indicate increasing runoff. However, the trend in GrIS 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.

In Fig. 4a, 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 link 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. For Kangerlussuaq, the runoff significantly increased by ~55% from 1978/79 through 2007/08 ($R^2 = 0.30$, $p < 0.01$). Further, for the year 2006/07, record modeled Kangerlussuaq runoff of 1.76 km^3 w.eq. occurred (Table 3). The average variations in the increasing Kangerlussuaq runoff from 1978/79 through 2007/08 closely follows the overall variations in the satellite-derived GrIS surface melt (Fig. 4a), where 64% of the simulated runoff variation was explained by satellite-derived melt area (Fig. 4b). However, the simulated runoff does not take into account year-to-year runoff variations due to all possible changes in GrIS freshwater storage. 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 substantial 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.

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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 with effects of 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. Further, the overall trend in both net precipitation and runoff increased significantly, resulting in a ~ 10% reduction in the percentage of catchment runoff explained by runoff from the GrIS. The increasing Kangerlussuaq runoff is strongly correlated with the overall pattern of the satellite-derived GrIS surface melt, illustrating a clear link (64% of the simulated runoff variation was explained by satellite-derived melt area) between surface melt conditions and runoff.

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Table 1. Meteorological input data for the Kangerlussuaq simulations. Meteorological station data on the GrIS (S5, S6, and S9) were provided by Utrecht University, and coastal meteorological station data (K; Kangerlussuaq) by the Danish Meteorological Institute (DMI). For further information about the S-stations see e.g., van den Broeke et al. (2008a).

Meteorological station name	Location	Grid	Data time period for runoff simulations	Altitude (m a.s.l.)	Parameters
K	Town Kangerlussuaq	67°01′ N, 50°42′ W*	1 Sep 1979–31 Aug 2008	50	Air temperature, relative humidity, wind speed, wind direction, and corrected precipitation
S5	Ice Sheet	67°06′ N, 50°07′ W	1 Sep 2006–31 Aug 2007	490	Air temperature, relative humidity, and wind speed
S6	Ice Sheet	67°05′ N, 49°23′ W	1 Sep 2006–31 Aug 2007	1020	Air temperature, relative humidity, and wind speed
S9	Ice Sheet	67°03′ N, 48°14′ W	1 Sep 2006–31 Aug 2007	1520	Air temperature, relative humidity, and wind speed

* The meteorological station in Kangerlussuaq was moved 660 m, with no change in elevation, in 2004, to the present location at the airport (50 m a.s.l.) (personal communication, Juncher Jensen, Danish Meteorological Institute, 2009). No air temperature correction was made to the Kangerlussuaq meteorological data.

Table 2. User-defined constants used in the SnowModel simulations (see Liston and Sturm (1998) for parameter definitions).

Symbol	Value	Parameter
C_v		Vegetation snow-holding depth (equal surface roughness length, Z_0) (m)
	0.50	–Barren bedrock/vegetation
	0.50	–River valley
	0.01	–Ice/snow
F	500.0	Snow equilibrium fetch distance (m)
U_{*t}	0.25	Threshold wind-shear velocity ($\mathrm{m\,s^{-1}}$)
dt	1	Time step (daily)
$dx=dy$		Grid cell increment (km)
	0.5	–Greenland Ice Sheet Kangerlussuaq simulation area
α		Surface albedo
	0.5–0.8	–Snow (variable snow albedo according to surface snow characteristics)
	0.4	–Ice
ρ		Surface density ($\mathrm{kg\,m^{-3}}$)
	280	–Snow
	910	–Ice
ρ_s	550	Saturated snow density ($\mathrm{kg\,m^{-3}}$)

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Table 3. Rank-ordered Kangerlussuaq catchment net precipitation (defined as P–(SU+ET)), runoff (R), change in storage (ΔS), and catchment summer (June, July, and August) air temperature anomaly for 1978/79 through 2007/08, where P is the precipitation input from snow and rain (and possible condensation), ET is evapotranspiration (liquid-to-gas phase [atmosphere] flux of water vapor), and SU is sublimation, including blowing-snow sublimation (snow blowing; solid-to-gas phase with no intermediate liquid stage). The yearly water balance equation for the catchment can be described by: $P-(ET+SU)-R\pm\Delta S=0\pm\eta$. Here, η is the water balance discrepancy (error).

Rank	Net precipitation (P-(SU+E)) (km^3 w.eq. y^{-1})	Runoff (R) (km^3 w.eq. y^{-1})	Change in storage (ΔS; SMB) (km^3 w.eq. y^{-1})	Catchment summer air temperature anomaly (JJA) (°C)
1	1.93 (2004/05)	1.76 (2006/07)	0.97 (1982/83)	1.89 (2003)
2	1.79 (1990/91)	1.31 (1998/99)	0.78 (2004/05)	1.58 (2000)
3	1.76 (2003/04)	1.27 (2005/06)	0.70 (1995/96)	1.43 (2001)
4	1.70 (2000/01)	1.23 (2003/04)	0.62 (1990/91)	1.42 (2007)
5	1.61 (2006/07)	1.20 (2001/02)	0.60 (1996/97)	1.13 (2008)
26	1.02 (1980/81)	0.75 (1988/89)	−0.14 (2006/07)	−1.08 (1996)
27	1.01 (1983/84)	0.67 (1995/96)	−0.19 (1984/85)	−1.53 (1979)
28	0.94 (1984/85)	0.66 (1978/79)	−0.22 (1998/99)	−1.90 (1992)
29	0.88 (1989/90)	0.62 (1982/83)	−0.29 (1989/90)	−2.89 (1983)
30	0.59 (1979/80)	0.58 (1991/92)	−0.39 (1979/80)	−3.18 (1982)
30-year average and standard deviation	1.28(± 0.31)	1.02(± 0.25)	0.26(± 0.34)	0.00(± 1.26)

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Increasing runoff from the Greenland Ice Sheet at Kangerlussuaq

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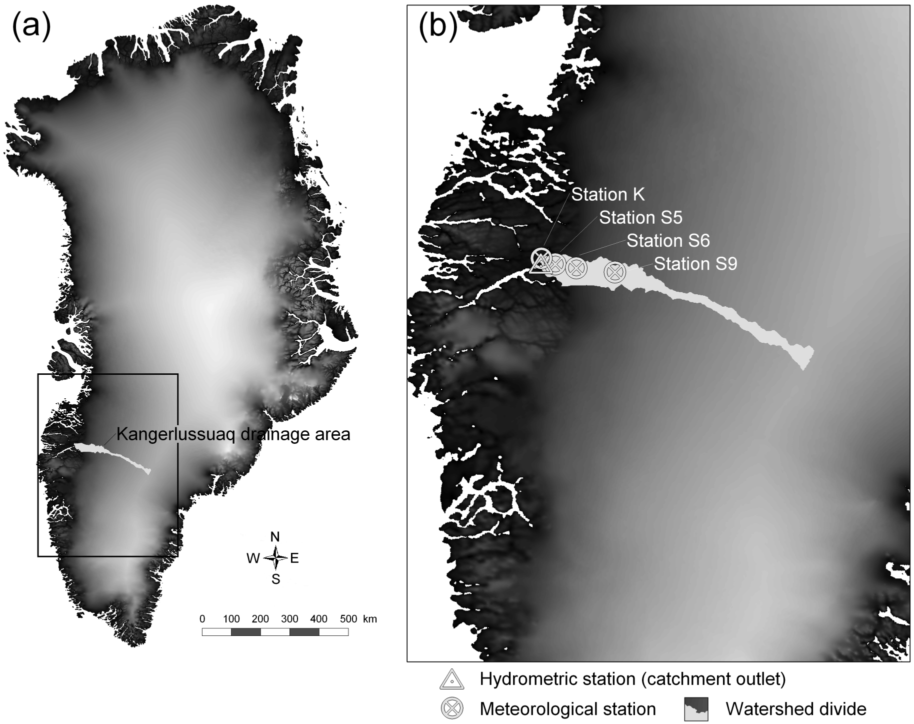

Fig. 1. **(a)** Greenland including the Kangerlussuaq drainage area (6130 km^2) in West Greenland; **(b)** simulation area with topography (gray shades elevation), the four meteorological stations: Station K (50 m a.s.l.), S5 (490 m a.s.l.), S6 (1020 m a.s.l.), and S9 (1520 m a.s.l.), the hydrometric station at the catchment outlet, and the catchment watershed divide. The catchment watershed divide was established in River Tools based on a DEM by Bamber et al. (2001).

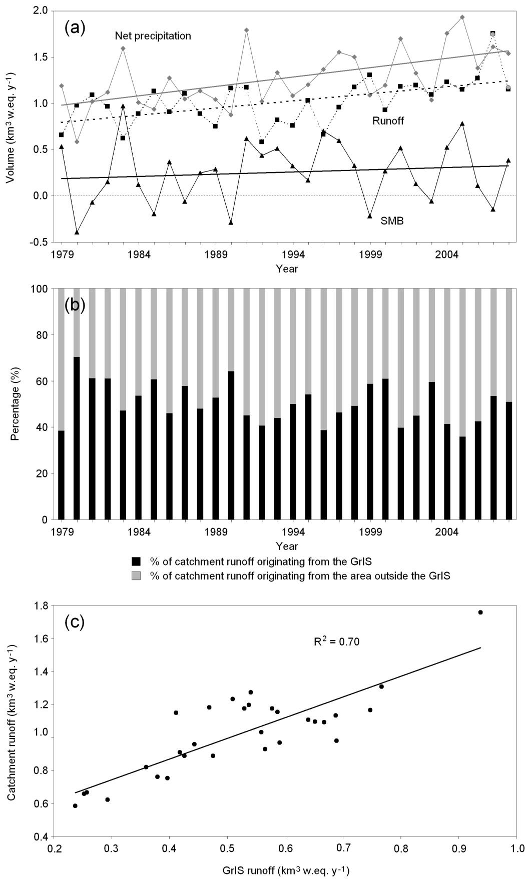

Fig. 2. **(a)** Kangerlussuaq net precipitation, runoff, and change in storage (ΔS; SMB) series for 1978/79 through 2007/08. For 2007 and 2008, the observed June through August runoff is further illustrated based on data from Mernild et al. (2009); **(b)** percentage of catchment runoff explained by GrIS runoff and by precipitation and snowmelt; and **(c)** relationship between GrIS runoff and Kangerlussuaq catchment runoff.

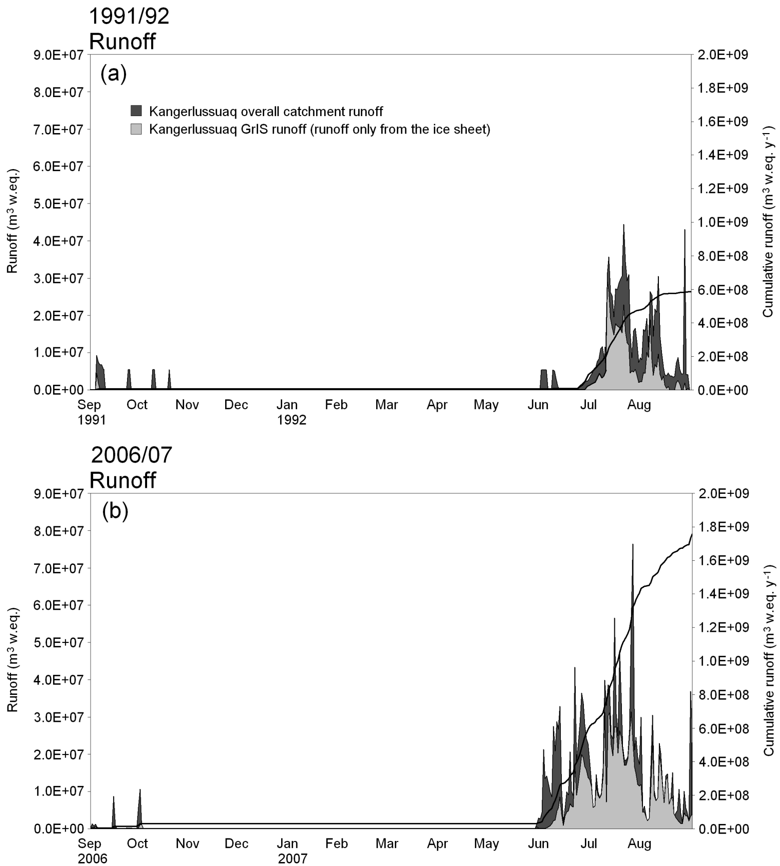

Fig. 3. **(a** and **b)** Time series of daily modeled runoff for the Kangerlussuaq part of the GrIS and for the Kangerlussuaq drainage area for 1991/92 (the year with the lowest annual cumulative runoff) and 2006/07 (highest cumulative runoff). The period from September through August follows the fixed GrIS mass-balance year.

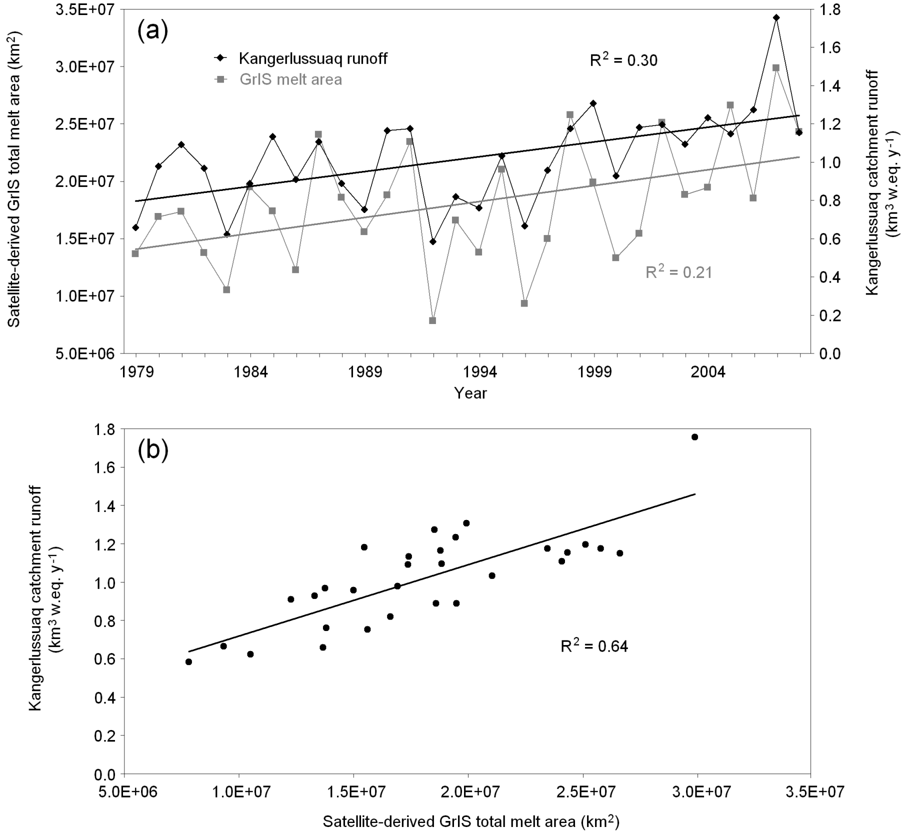

Fig. 4. (a) Time series of Kangerlussuaq simulated runoff and passive microwave satellite-derived GrIS total melt extent area (satellite data provided by CIRES, University of Colorado at Boulder) for 1979 through 2008; and **(b)** relation between satellite-derived GrIS total melt area and Kangerlussuaq catchment runoff. Without the extreme 2006/07 anomaly the R^2 was 0.57.