

# Simulated Internal Storage Buildup, Release, and Runoff from Greenland Ice Sheet at Kangerlussuaq, West Greenland

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## Abstract

This study focused on simulated glacier surface conditions (simulated Surface Melt and liquid Precipitation available for supra-, en-, sub-, and proglacial flow processes [after vertical percolation and potential storage within the snowpack] [henceforth SMP]), internal water storage and release, and runoff from the Kangerlussuaq drainage area of the Greenland Ice Sheet (GrIS), West Greenland, for the period 2006/2007 to 2007/2008. GrIS winter accumulation and summer ablation processes, including SMP, was simulated on both daily and hourly time steps. Using hourly meteorological driving data produced more realistic meteorological conditions instead of daily-averaged data, in relation to snow and melt threshold surface processes, and produced 9–17% higher annual cumulative SMP. The difference between simulated SMP and observed catchment runoff showed a decreasing lag time through the summer, and a drainage system storage buildup through approximately June and early July of up to  $0.29 \times 10^9 \text{ m}^3$ , and a storage release through approximately late July and August of up to  $0.25 \times 10^9 \text{ m}^3$ . The simulated total Kangerlussuaq SMP for 2006/2007 and 2007/2008, indicated a reduction of 30%. This reduction in SMP occurred simultaneously with the reduction in the overall pattern of satellite-derived GrIS surface melt from 2007 to 2008.

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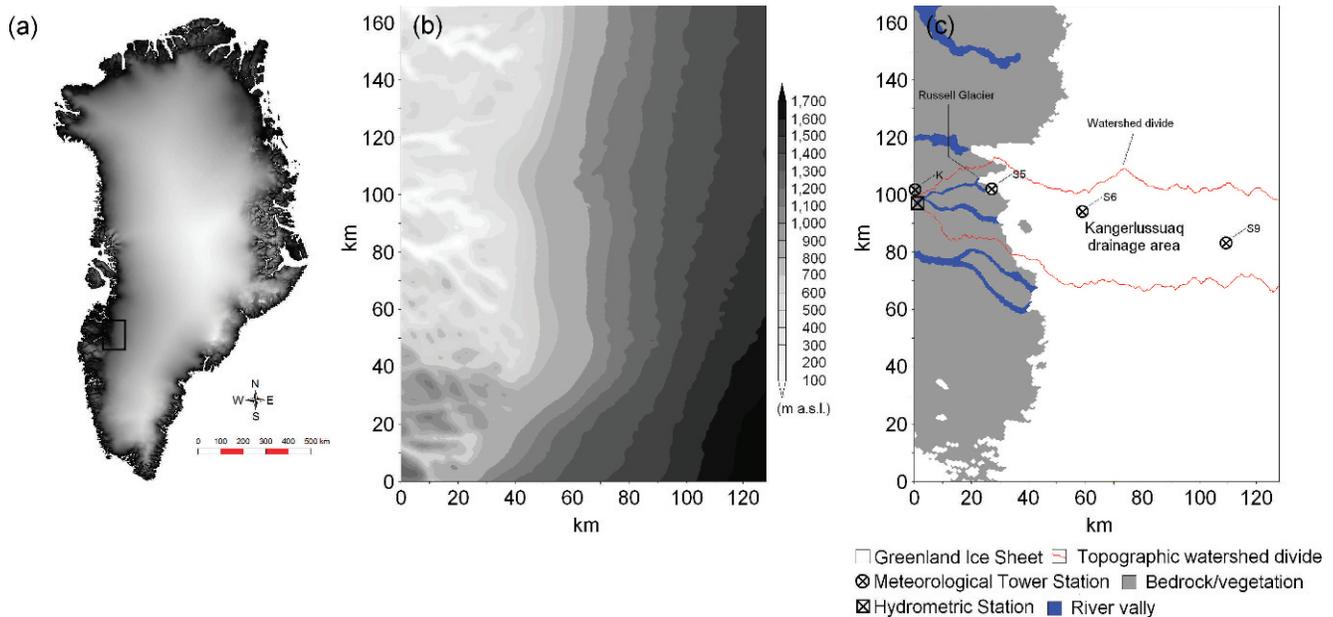
## Introduction

The Greenland Ice Sheet (GrIS), from a hydrological perspective, is a reservoir of freshwater stored in the form of ice. On the GrIS, a response to climate change has already been observed in different ways by an accelerating surface melt extent, mass loss, and freshwater runoff (Janssens and Huybrechts, 2000; Zwally et al., 2002; Johannessen et al., 2005; Box et al., 2006; Fettweis, 2007; Mernild et al., 2008, 2011; Steffen et al., 2008; Ettema et al., 2009; Hanna et al., 2009; Van den Broeke et al., 2009; Fettweis et al., 2011). In spite of the need for information about GrIS freshwater runoff, only a few high-resolution runoff observations are available of water exiting the GrIS (Mernild and Hasholt, 2009). This measurement gap is particularly notable in the context of observed variations in snow and ice sheet surface melt, and possible changes in runoff storage and release by internal deformation of the GrIS drainage system (Stenborg, 1970; Jansson et al., 2003; Pimentel and Flowers, 2011). Further, such runoff observations represent an integrated response of the upstream watershed to precipitation and other hydrometeorological processes, and are required to estimate the impact of catchment runoff on the arctic marine ecosystem and for obtaining knowledge about the onset, duration, and intensity of runoff and hydrological response throughout the year. High-resolution runoff observations are also useful, for example, to support model simulations of freshwater resource availability, for defining controls on global eustatic sea level rise, and for quantifying runoff effects on modifying ocean salinity (Dowdeswell et al., 1997; ACIA, 2005; IPCC, 2007). Such high-resolution runoff observations have been maintained at the Kangerlussuaq (Søndre Strømfjord) outlet, West Greenland, since June 2007, providing information on stage and runoff from a sector of the GrIS

(Mernild and Hasholt, 2009). The Kangerlussuaq outlet is one of only a few locations for observing GrIS runoff because of the stable bedrock cross sections.

Modeling the GrIS surface mass balance (SMB) is relatively well understood and documented in several studies (Fettweis, 2007; Hanna et al., 2007; Ettema et al., 2009; Mernild et al., 2009a). The mechanisms that connect climate, the GrIS SMB, ice dynamics, and internal ice sheet hydrology, e.g., routing and storage of meltwater and liquid precipitation through glacier ice, and transforming the input contributions into a runoff hydrograph at the ice sheet terminus based on seasonal changes in hydrological response and delay, are still weakly understood (Parizek and Alley, 2004; Lemke et al., 2007; van den Broeke et al., 2008a; Nick et al., 2009). In spite of this, there is growing recognition that accurate representations of SMB, internal drainage and storage, and flow processes are essential to realistically assess the impact of climate changes on the GrIS and its runoff. Simple and crude conceptual runoff models have described glaciers as porous media and as a system of linear reservoirs, with different storage properties (e.g., Campbell and Rasmussen, 1973; Jansson et al., 2003; Mernild and Hasholt, 2006). With the purpose of simulating runoff from glacierized basins, these models omit many of the key physical processes.

The goal of this study is to apply a well-tested, state-of-the-art surface modeling system—SnowModel (Liston and Elder, 2006a; Mernild et al., 2006a)—to the Kangerlussuaq region, West Greenland, to improve our quantitative understanding of the Kangerlussuaq drainage area water balance components, storage, and changes. Therefore, simulated SMP (Surface Melt and liquid Precipitation available for glacial flow [after vertical percolation and potential storage within the snowpack] and terrestrial flow



**FIGURE 1.** (a) The Kangerlussuaq region in western Greenland, including the simulation area (21,250 km<sup>2</sup>); (b) simulation area with topography (gray shades, 100-m contour interval); and (c) Kangerlussuaq drainage area land cover characteristics including 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 of the Kangerlussuaq drainage area (6130 km<sup>2</sup>), and the surface watershed divides. The surface watershed divide is estimated based on the program RiverTools (<http://www.rivertools.com/>).

processes) values were compared with observational runoff data sets at the catchment outlet. Winter processes related to snow accumulation, snow redistribution by wind, and snow sublimation and summer processes related to sublimation, evaporation, and melt were simulated based on meteorological station data both on and outside the GrIS. SnowModel routines were tested against independent GrIS snow depth and catchment-outlet runoff observations. The model simulations were performed both on daily and hourly time steps for the 2-year observation period (2006/2007 through 2007/2008). In order to achieve these objectives: (1) the differences in simulated SMP were shown based on daily and hourly time steps, to indicate the variation in daily-averaged and hourly high-resolution outputs; (2) modeled SMP were compared with available independent observational runoff data sets at the catchment outlet to illustrate and quantify seasonal freshwater storage and storage release within the flow system, and changes in lag time during the melt season; and (3) satellite-derived GrIS surface melt extent was compared with modeled SMP, to illustrate whether an annual change in GrIS melt extent equals an annual change in Kangerlussuaq SMP.

### Study Area

The Kangerlussuaq drainage area (6130 km<sup>2</sup>) is located on the west coast of Greenland (67°N latitude, 50°W longitude) (Fig. 1, part a) and provides drainage for a sector of the GrIS. The runoff measurement site is located at the bottom of the Kangerlussuaq Fjord, an average of 22 km downstream from the terminus of the Russell Glacier (Fig. 1).

The simulated Kangerlussuaq region (21,250 km<sup>2</sup>) (Fig. 1) covers the western part of the GrIS (14,780 km<sup>2</sup>) and 6470 km<sup>2</sup> of the proglacial landscape. The simulation area is characterized by elevations that range from sea level to ~1800 m a.s.l. (Fig. 1, part b). The land cover is dominated by glacier ice (88%) in the upper parts of the terrain, and bare bedrock/vegetation and river valleys (12%) in the lower parts of the drainage area (Fig. 1, part c).

Four meteorological stations are located within the simulation domain, with three of them on the GrIS (Fig. 1, part c; Table 1). Station Kangerlussuaq (hereafter referred to as Station K) (67°01'N, 50°42'W; 50 m a.s.l.; a standard synoptic Danish Meteorological Institute (DMI) meteorological station), is located within the town of Kangerlussuaq. Station K is representative of proglacial conditions, influenced by the Kangerlussuaq Fjord. Station 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. The mean equilibrium line altitude (ELA; defined as the spatially averaged elevation of the equilibrium line, defined as the set of points on the glacier surface where the net mass balance is zero) is ~1530 m a.s.l., located near Station S9 (van de Wal et al., 2005; van den Broeke et al., 2008b).

The mean annual observed air temperature for the Kangerlussuaq simulation domain (2006/2007–2007/2008) was -6.7 °C. Mean annual relative humidity was 66%, and mean annual wind speed was 4.4 m s<sup>-1</sup>. The corrected mean total annual precipitation (TAP) for the region was 234 mm w.e. y<sup>-1</sup> (corrected after Allerup et al., 1998, 2000). Observed runoff from May through September varied from 1.77 × 10<sup>9</sup> m<sup>3</sup> in 2007 to 1.28 × 10<sup>9</sup> m<sup>3</sup> in 2008 (Mernild and Hasholt, 2009), and from June through August from 1.72 × 10<sup>9</sup> m<sup>3</sup> in 2007 to 1.21 × 10<sup>9</sup> m<sup>3</sup> in 2008 (Tables 4 and 5).

### Method

#### SNOWMODEL DESCRIPTION

SnowModel (Liston and Elder, 2006a; Mernild et al., 2006a) is a spatially distributed snow-evolution modeling system designed for landscapes where snow and glaciers are present. It is an aggregation of five submodels: MicroMet (Liston and Elder, 2006b), EnBal (Liston, 1995; Liston et al., 1999), SnowPack (Liston and Hall, 1995), SnowTran-3D (Liston and Sturm, 1998,

TABLE 1

Meteorological input data for the Kangerlussuaq SnowModel simulations. Meteorological station data on the GrIS (S5, S6, and S9) were provided by the 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). The abbreviations for the meteorological parameters are: Tair (air temperature), Rh (relative humidity), Ws (wind speed), Wd (wind direction), and Pc (corrected precipitation (after Allerup et al., 1998, 2000)).

Meteorological station			Data time period for runoff			
name	Location	Grid	simulations	Altitude (m a.s.l.)	Parameters	
K	Town Kangerlussuaq	67°01'N, 50°42'W	1 Sep 2006–31 Aug 2008	50	Tair, Rh, Ws, Wd, and Pc	
S5	Ice Sheet	67°06'N, 50°07'W	1 Sep 2006–31 Aug 2008	490	Tair and Ws	
S6	Ice Sheet	67°05'N, 49°23'W	1 Sep 2006–31 Aug 2008	1020	Tair and Ws	
S9	Ice Sheet	67°03'N, 48°14'W	1 Sep 2006–31 Aug 2008	1520	Tair and Ws	

2002; Liston et al., 2008), and SnowAssim (Liston and Hiemstra, 2008). MicroMet defines meteorological conditions; EnBal calculates the surface energy balance; SnowPack simulates snow depth, water-equivalent evolution, including water percolation when the saturated snow density is reached. If the snow temperature is below freezing, any liquid water/percolation refreezes and is stored in the snow (in SnowModel the term ‘runoff’ has previously been used when water flows from the bottom of the snowpack into the supra-, en-, and subglacial or to the proglacial drainage system (conceptual figures of possible flow paths are illustrated in Figure 2 both for the beginning and the end of the ablation period). Here, the term ‘SMP’ (Surface Melt and liquid Precipitation available for glacial flow (after vertical percolation and potential storage within the snowpack) and terrestrial flow processes) is used instead; SnowTran-3D simulates snow redistribution by wind; and SnowAssim assimilates available snow observations to generate simulated snow distributions which are equivalent to measured distributions. SnowModel was originally developed for snow landscapes. It was afterwards modified by Mernild et al. (2006a) for glacier landscapes to simulate glacier SMB, including glacier-ice melt, and further by Mernild et al. (2010) to simulate variable snow albedo (for an overall description of SnowModel, its submodels, and modifications—the physics of the systems—see e.g., Liston et al. [2008], and Mernild and Liston [2010] and references therein). SnowModel is a surface model simulating first-order effects of variations and changes in atmospheric forcing; therefore, routines for glacio-dynamic and glacio-sliding routines are not included in the calculations. Consequently, SnowModel does not include changes in the GrIS area, elevation, and size, or melting from geothermal heating. Further, SnowModel is not dealing with meltwater routing, like horizontal flow processes at the base of the snowpack, and over the bare ice surface when the snowpack has ablated, nor possible en-, sub-, and pro-glacial flow processes. The evolution of the internal drainage system was also not included in the simulations, even though in the natural system it does influence the outlet hydrograph and the cumulative runoff.

#### SNOWMODEL INPUT

Spatially distributed fields of surface topography and land cover, and temporally distributed point meteorological data are required as input for SnowModel. Meteorological data of air temperature, relative humidity, wind speed, wind direction, and precipitation were obtained from all four meteorological tower stations located within the domain for both 2006/2007 and 2007/2008. The simulations span the 2-year runoff observation period 1 September 2006 through 31 August 2008 (approximately following the annual GrIS mass-balance year from September through

August), and were performed on both daily and hourly time steps. Air temperature observations from S5, S6, and S9 provided mean monthly lapse rates. A variation in monthly temperature lapse rate occurred from  $-8.6\text{ }^{\circ}\text{C km}^{-1}$  in October to  $-4.6\text{ }^{\circ}\text{C km}^{-1}$  in July (Table 2). The mean annual Kangerlussuaq GrIS lapse rate of  $-6.7\text{ }^{\circ}\text{C km}^{-1}$  was slightly higher than the average western GrIS lapse rate of  $-7.8\text{ }^{\circ}\text{C km}^{-1}$  determined by Steffen and Box (2001).

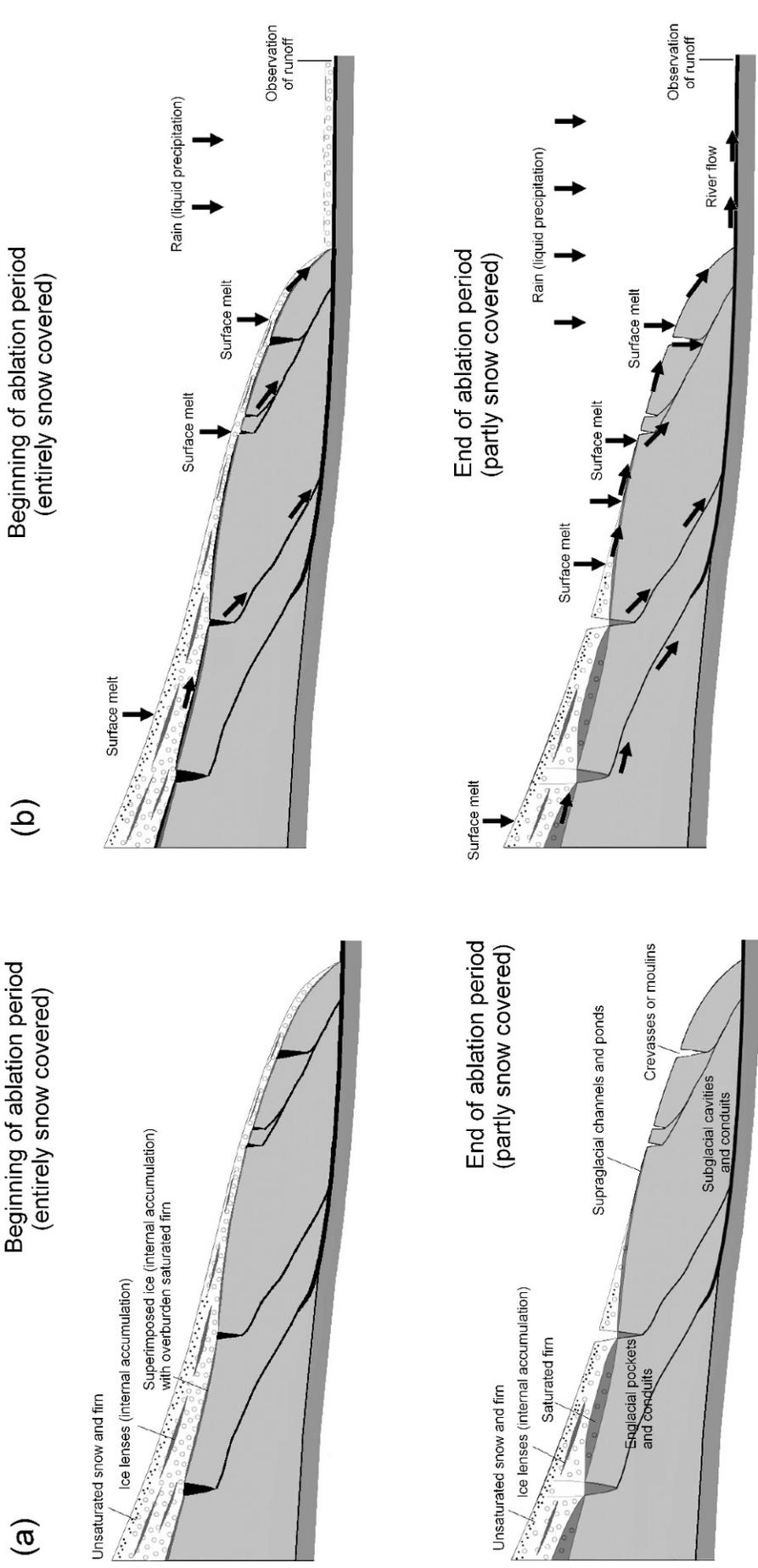
Solid and liquid precipitation measurements at the DMI meteorological station (Fig. 1, part c; Table 1) were calculated from Helman–Nipher shield observations corrected according to Allerup et al. (1998, 2000): since precipitation gauges underestimate solid and liquid precipitation due to aerodynamic errors, corrections are needed (e.g., Yang et al, 1998).

Spatially distributed fields of surface topography were provided by Bamber et al. (2001), with image-derived corrections of Scambos and Haran (2002), and aggregated (in a Geographical Information System [GIS]) from the original 625 m grid-cell digital elevation model (DEM) to a 500 m grid-cell DEM covering a  $128 \times 166\text{ km}$  simulation domain ( $21,250\text{ km}^2$ ; the Kangerlussuaq region) (Fig. 1, part b). The GrIS terminus was estimated using satellite images (Google Earth, Image 2009). Each grid cell within the domain was assigned a U.S. Geological Survey Land Use/Land Cover System class according to the North American Land Cover Characteristics Database, Version 2.0. The user-defined SnowModel constants have already been described in Mernild et al. (2009b) (see also Liston and Sturm [1998] for parameter definitions).

#### SNOWMODEL CALIBRATION, VALIDATION, AND UNCERTAINTY

In order to assess the performance of SnowModel, simulated meteorological distributions, snow depths, snow and ice surface melt, and glacier mass balance were tested against independent observations not used in SnowModel. Distributed MicroMet modeled data have been compared against meteorological station data both on and outside the GrIS; verification of MicroMet simulated meteorological data indicate substantial correlation with independent observed meteorological data (Mernild et al., 2008; Mernild and Liston, 2010). Accumulation and ablation values simulated in SnowModel were tested using independent observations of snow pit depths; glacier mass balances; photographic time lapses; and satellite images also from in and outside the GrIS (e.g., Mernild et al., 2009b, 2010), indicating an error of 10–25% between simulated and observed values.

For this Kangerlussuaq study, the end-of-winter (31 May, also recognized as the end of the accumulation period) simulated snow depth was compared with Station S9 observed point snow depth (provided by Campbell SR-50), and the simulated cumulative summer (June through August) SMP were compared



**FIGURE 2.** (a) A conceptual cross-section figure of the lower part of the Greenland Ice Sheet (GrIS) margin and the proglacial landscape at the beginning and at the end of the ablation period; and (b) the possible hydrological flow paths for simulated Surface Melt and liquid Precipitation (SMP) both at the beginning and at the end of the ablation period. The arrows indicate hydrometeorological and hydrological processes (surface melt, rain, and river flow) and different theoretical supra-, en-, sub-, and proglacial freshwater flow directions. Also illustrated is the location of a hydrometric station downstream the GrIS in the proglacial landscape (modified after Röthlisberger and Lang, 1987; Jansson et al., 2003; Mernild et al., 2006b).

TABLE 2

Mean monthly air temperature lapse rates for the GrIS Kangerlussuaq area, based on data from the transect between the meteorological stations S5 (490 m a.s.l.), S6 (1020 m a.s.l.), and S9 (1520 m a.s.l.). See Figure 1, part c, for meteorological station locations and Table 1 for station information.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean
Lapse rates ( $^{\circ}\text{C km}^{-1}$ )	-6.3	-7.0	-7.3	-5.6	-7.5	-5.2	-4.6	-4.8	-7.8	-8.6	-8.1	-7.4	-6.7

with observed catchment-outlet runoff entering directly into the Kangerlussuaq Fjord (Fig. 1, part c). The Station S9 point snow depth was measured on 31 May and used to verify the SnowModel simulated snow depth (simulated based on the 500 m grid-cell) (Table 3). The initial simulated snow depth was, on average, different by  $\sim 20\%$  (140 mm w.e.) for 2003/2004–2006/2007, and up to  $\sim 30\%$  (220 mm w.e.) for 2003/2004 (Table 3) compared to the Station S9 observed point snow depth. These uncertainties are expected to be due to uncertainties associated with: (1) model inputs, especially solid precipitation, which is difficult to measure precisely in windy environments because of aerodynamic errors at the precipitation gauging station (e.g., Yang et al., 1998; Liston and Sturm, 2002, 2004; Serreze and Barry, 2005), and variations in precipitation conditions between the proglacial Kangerlussuaq measured precipitation and GrIS observed snow depth; (2) unrepresented or poorly represented processes in SnowModel, together with the use of a 500 m grid-cell DEM; and (3) uncertainties related to point snow depth observations. To correct these deficiencies, the iterative snow adjustment routines from SnowAssim were used and yielded a final simulated Station S9 snow depth on 31 May that was within the stop criterion for the iterations (1%; Table 3) (for additional information on the iterative snow adjustment routine, see e.g., Mernild et al., 2006a; Liston and Hiemstra, 2008).

The catchment outlet runoff was observed for the 2007 and 2008 runoff seasons (Mernild and Hasholt, 2009). Stage and discharge measurements were used to develop a stage-discharge relationship ( $r^2 = 0.91$ ) and to convert the stage measurements into a river runoff time series. The relationships are expected to have an uncertainty of 10–15% (Mernild and Hasholt, 2009). For 2007 and 2008 (before calibration), the cumulative simulated SMP differs 60% and 50% from observed runoff values, respectively (Tables 4 and 5; simulations based on input data from all four meteorological stations and on daily time step). For 2007 and 2008, the cumulative simulated SMP (based on daily time step) were therefore calibrated to be within 1% of the cumulative observed catchment runoff (Tables 4 and 5; Figs. 3, part a; and 4, part a). The calibration was conducted by tuning various

parameters in SnowModel like, e.g., snow and glacier surface albedo, and saturated snow density (for information about the parameters see Liston and Elder, 2006a, 2006b).

In Figure 3 (parts b and c), daily time series of modeled SMP, and observed runoff for 2007, are illustrated. In Figure 3 (part c), an acceptable variability is illustrated, with  $r^2$ -values of 0.44 (daily time step) and 0.58 (5-day back running average). The choice of the 5-day back-running average for June through August produced the highest  $r^2$ -value (note that the model does not include runoff routing and temporary storage routines for the GrIS and proglacial landscape), compared to the 2-day back-running average ( $r^2 = 0.46$ ), 3-day (0.48), 4-day (0.55), and 6-day (0.57). On an hourly basis, the 2007  $r^2$ -value for the 5-day/120-hour back-running average was 0.62 (Fig. 5, part c). In Figure 4 (parts b and c), daily time series of modeled SMP, and observed runoff for 2008 are illustrated. For the 2008 simulated and observed time series, the  $r^2$ -values were 0.45 (daily time step) and 0.50 (5-day back running average). On an hourly basis, the 2008  $r^2$ -value for the 5-day/120-hour back-running average was 0.52 (Fig. 5, part d). A higher  $r^2$ -value occurred for hourly simulations than for daily simulations, because high-resolution time step simulations produced more realistic meteorological and surface melt conditions than the daily-averaged data, in relation to snow and melt threshold surface processes and delay processes in the snow.

## Results and Discussion

### HOURLY AND DAILY SIMULATIONS

In contrast to hourly simulations, threshold processes like blowing snow, snowmelt, ice-melt, and meltwater flow through the snowpack may not be realistically represented by the smoothed atmospheric forcing conditions used in daily time step simulations. Figures 3 (part b), 4 (part b), and 5 (parts a and b), display daily and hourly time step modeled SMP for the Kangerlussuaq drainage area for the 2007 and 2008 observation period (June through August). These figures illustrate: (1) fewer variations and fluctuations in daily modeled SMP values, compared with hourly

TABLE 3

Observed and modeled snow depth for Station S9 at the end of winter (31 May; recognized as the end of the accumulation period) (for station specifications, see Fig. 1, part c, and Table 1).

Year	Observed end-of-winter (31 May) snow depth at Station S9 (mm) (van den Broeke et al., 2008b)	Modeled end-of-winter (31 May) snow depth at Station S9 based on precipitation data from Station K in Kangerlussuaq (mm)	Difference in observed and modeled end-of-winter (31 May) snow depth at Station S9 based on precipitation data from Station K in Kangerlussuaq (mm and %)	Modeled end-of-winter (31 May) snow depth at Station S9, based on iterative precipitation adjustment routines described in Mernild et al. (2006a) and Liston and Hiemstra (2008) (mm)
2003/2004	830	1050	220	820
2004/2005	1090	1130	40	1090
2005/2006	870	960	90	870
2006/2007	730	930	200	730
Average and standard deviation	880 $\pm$ 150	1020 $\pm$ 90	140 $\pm$ 90 $\sim 20\%$	880 $\pm$ 150

TABLE 4

Observed runoff and simulated Surface Melt and liquid Precipitation (SMP) (daily and hourly time step) from the GrIS Kangerlussuaq drainage area for 2006/2007. Simulations are based on meteorological data from all four stations within the drainage area. The cumulative simulated SMPs from September 2006 through August 2007 are shown in bold.

	Time step	Period	Meteorological stations used for simulation	Cumulative runoff (m <sup>3</sup> ×10 <sup>9</sup> )	Difference in observed and simulated cumulative runoff (%)
Observed runoff at the catchment outlet (Mernild and Hasholt, 2009)	Daily	June through August 2007	—	1.72	—
Simulated SMP before calibration			K, S5, S6, and S9	2.86	60
Simulated SMP			K, S5, S6, and S9	1.72	<1
Simulated 5-day running average SMP			K, S5, S6, and S9	1.72	<1
Simulated 5-day running average SMP		September 2006 through August 2007	K, S5, S6, and S9	<b>1.76</b>	—
Simulated 5-day running average SMP	Hourly	September 2006 through August 2007	K, S5, S6, and S9	<b>2.06</b>	—

modeled SMP values; and (2) more smoothed daily SMP values compared with direct catchment runoff observations. Due to the smoothed tendency in daily time-step simulated values, daily simulations indicated a lower cumulative SMP of, 6–14% ( $0.09$ – $0.24 \times 10^9 \text{ m}^3$ ), compared with hourly time step simulated SMP for the observation period. For the entire 2006/2007 and 2007/2008 period (September through August), the tendency was similar but more pronounced, as a difference of 9–17% ( $0.11$ – $0.30 \times 10^9 \text{ m}^3$ ) occurred in cumulative SMP between daily and hourly simulations (Tables 4 and 5). A similar time step difference was illustrated in modeled SMP originating from the glacier ice on the GrIS. For 2006/2007, the modeled SMP (based on a daily time step) indicated that 55% ( $0.96 \times 10^9 \text{ m}^3$ ) originated from glacier ice. Similar simulations (hourly based) indicated that 64% ( $1.32 \times 10^9 \text{ m}^3$ ) originated from the glacier ice. A similar tendency was present for 2007/2008, but was less pronounced, as only 54% ( $0.69 \times 10^9 \text{ m}^3$ ) and 55% ( $0.76 \times 10^9 \text{ m}^3$ ) originated from the glacier ice. The use of less smoothed meteorological input data—hourly data instead of daily-averaged—indicated more realistic meteorological conditions related to threshold surface processes and a relatively higher annual cumulative SMP, a difference found to be between 9 and 17%.

#### STORAGE BUILDUP AND RELEASE, AND LAG TIME

A division of the 2007 and 2008 daily and hourly simulated SMP and observed runoff time series (June through August) is shown in Figures 3 (part b), 4 (part b), and 5 (parts c and d). The division was done to show the temporary seasonal GrIS freshwater storage (resulting in a delay) and release mainly by seasonal development of the drainage system. Time series were divided after Stenborg (1970) into sub-seasonal periods: Periods I, II, and III. Period I was characterized by simulated surface SMP exceeding the observed outlet runoff (indicating GrIS freshwater storage buildup). Period II simulated SMP almost equaled observed outlet runoff. Period III was where observed outlet runoff exceeded simulated SMP (indicating storage release). For Kangerlussuaq (daily time step), Period I occurred approximately from the beginning of the runoff season until the end of June/beginning of July; Period II, approximately from the end of June/beginning of July to the end of July; and Period III, approximately from the end of July to the end of the runoff season (Figs. 3, part b; and 4, part b). For Period I (daily time step), the storage buildup was  $0.29 \times 10^9 \text{ m}^3$  for 2007 and  $0.18 \times 10^9 \text{ m}^3$  for 2008, while for

TABLE 5

Observed runoff and simulated SMP (daily and hourly time step) from the GrIS Kangerlussuaq drainage area for 2007/2008. Simulations are based on meteorological data from all four stations within the drainage area. The cumulative simulated SMPs from September 2007 through August 2008 are shown in bold.

	Time step	Period	Meteorological stations used for simulation	Cumulative (m <sup>3</sup> ×10 <sup>9</sup> )	Difference in observed and simulated cumulative runoff (%)
Observed runoff at the catchment outlet (Mernild and Hasholt, 2009)	Daily	June through August 2008	—	1.21	—
Simulated SMP before calibration			K, S5, S6, and S9	1.82	50
Simulated SMF and P			K, S5, S6, and S9	1.21	<1
Simulated 5-day running average SMP			K, S5, S6, and S9	1.21	<1
Simulated 5-day running average SMP		September 2007 through August 2008	K, S5, S6, and S9	<b>1.27</b>	—
Simulated 5-day running average SMP	Hourly	September 2007 through August 2008	K, S5, S6, and S9	<b>1.38</b>	—

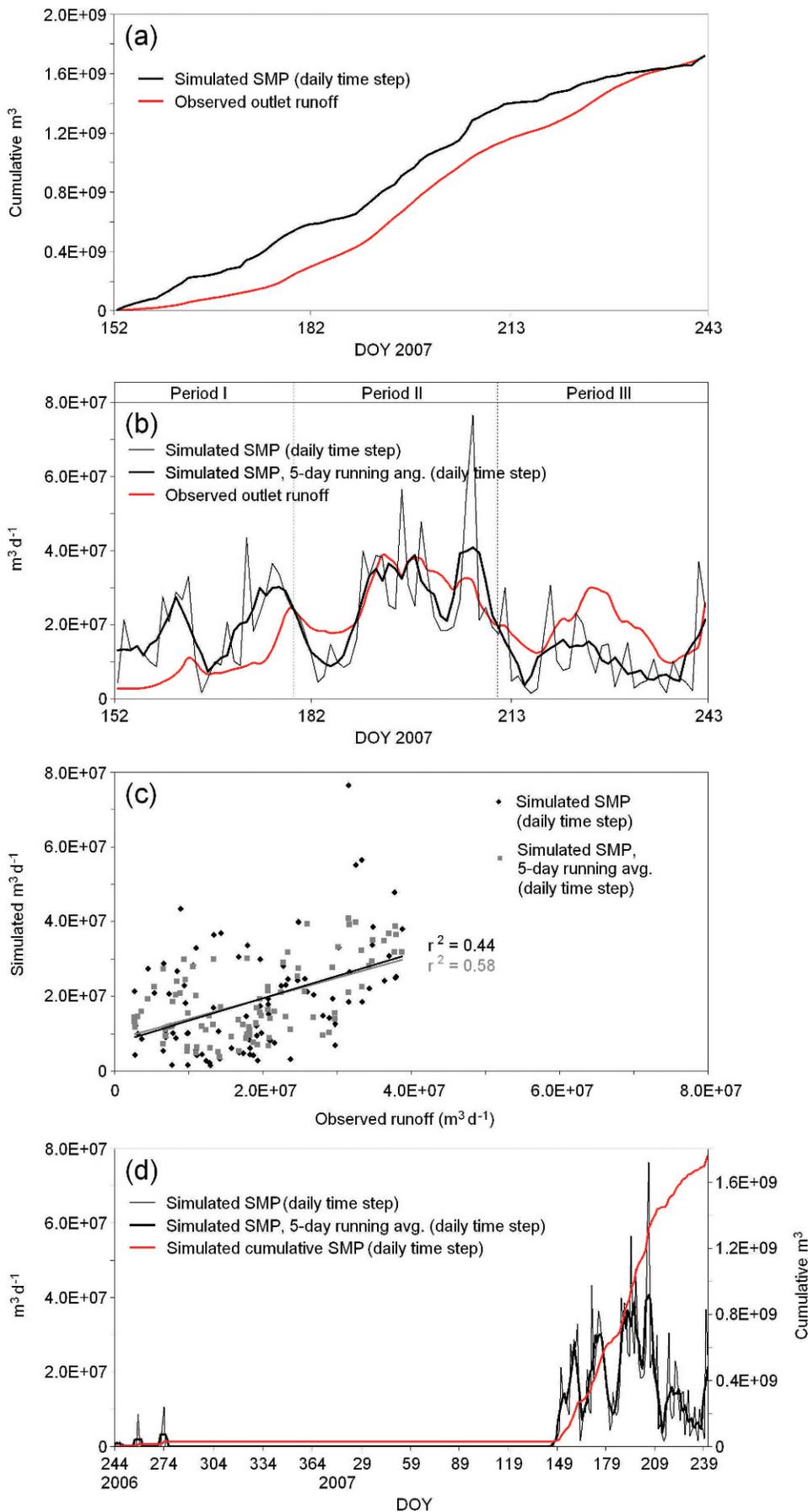


FIGURE 3. Daily mean of observed runoff and simulated SMP at the GRIS Kangerlussuaq drainage area for the 2006/2007 season: (a) cumulative observed runoff and simulated SMP from 1 June (DOY 152) through 31 August (DOY 243); (b) observed runoff, simulated SMP, and simulated 5-day back running average SMP; (c) a comparison (linear regression) between observed runoff and modeled SMP, and observed runoff and simulated 5-day back running average SMP; and (d) simulated SMP, simulated 5-day back running average SMP, including cumulative SMP from 1 September (DOY 244) to 31 August.

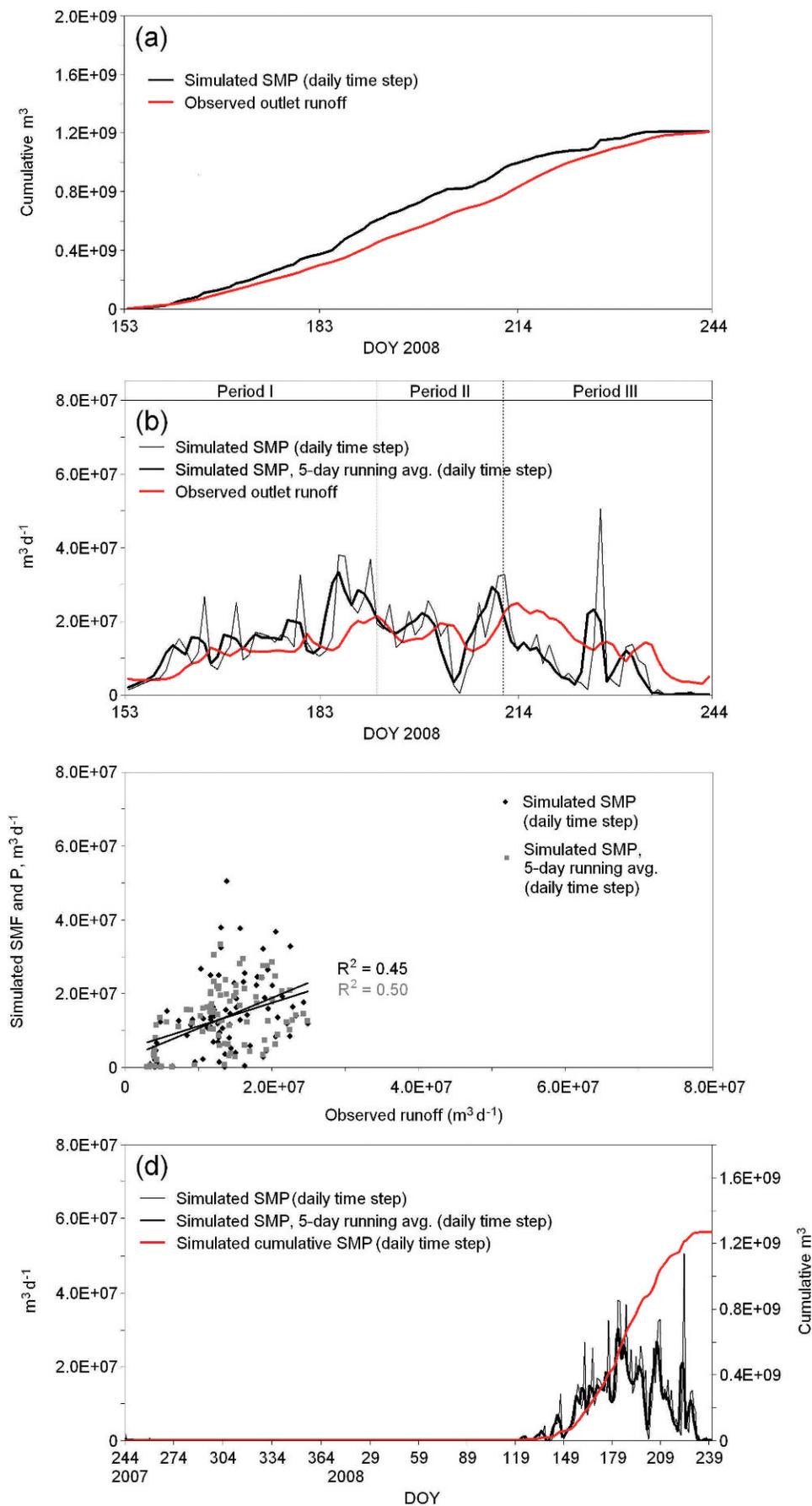


FIGURE 4. Daily mean of observed runoff and simulated SMP at the GrIS Kangerlussuaq drainage area for the 2007/2008 season: (a) cumulative observed runoff and simulated SMP from 1 June through 31 August; (b) observed runoff, simulated SMP, and simulated 5-day back running average SMP; (c) a comparison (linear regression) between observed runoff and modeled SMP, and observed runoff and simulated 5-day back running average SMP; and (d) simulated SMP, simulated 5-day back running average SMP, including cumulative SMP from 1 September (DOY 244) to 31 August.

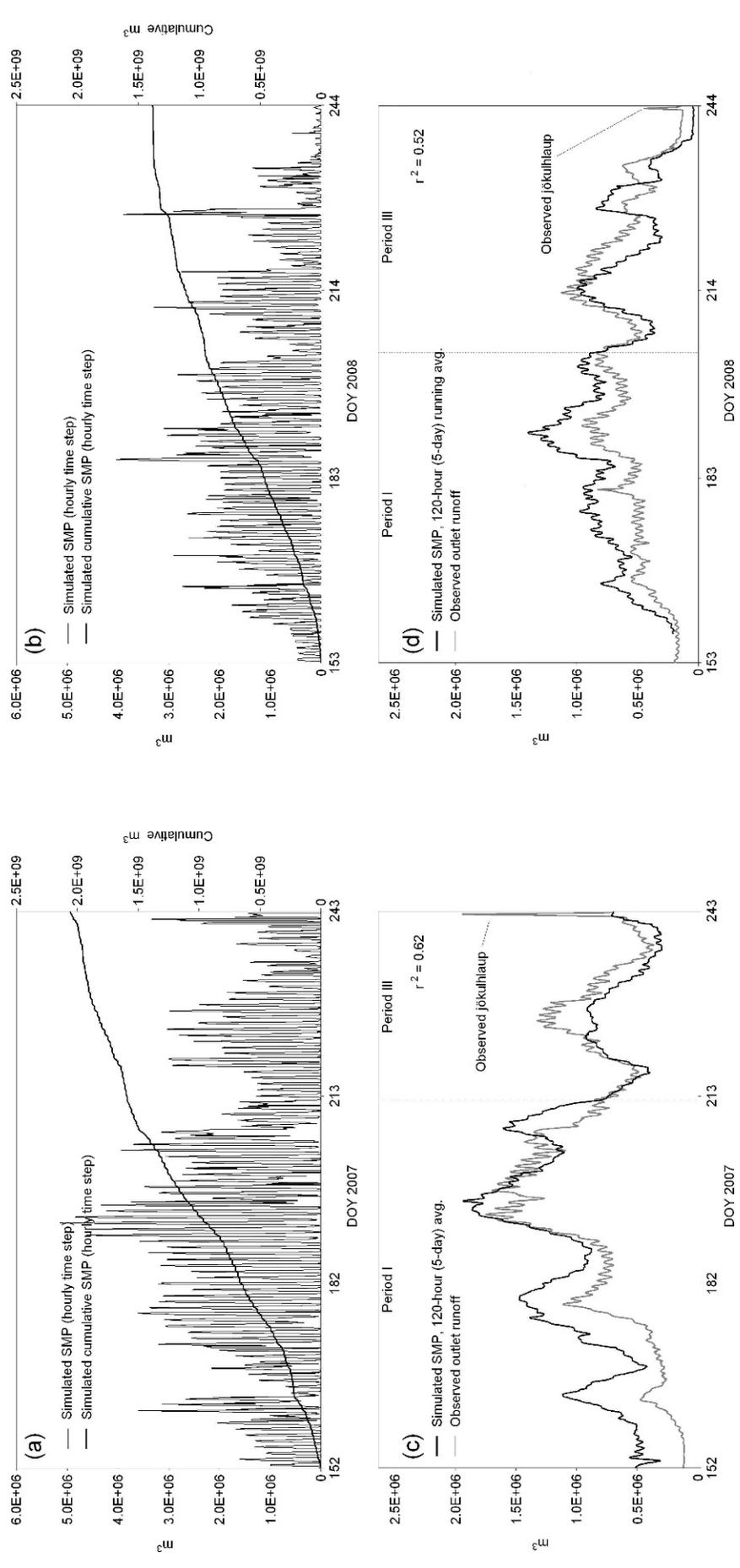


FIGURE 5. Hourly observed runoff, simulated SMP, and cumulative SMP at the GrIS Kangerlussuaq drainage area for the 2006/2007 and 2007/2008 seasons; (a) simulated SMP from 1 June through 31 August 2007; (b) simulated SMP from 1 June through 31 August 2008; (c) observed runoff and simulated 5-day running average SMP 1 June through 31 August 2007, including observed jökulhlaup 31 August (DOY 243); and (d) observed runoff and simulated 5-day running average SMP 1 June through 31 August 2008, including observed jökulhlaup 31 August (DOY 244).

**TABLE 6**

**Simulated freshwater storage buildup (Period I) and storage release (Period III) for the Kangerlussuaq drainage area (daily time step). For a division of the periods see Figures 3, part b, and 4, part b.**

Year	Time step	Freshwater storage buildup	Freshwater storage release
		(Period I) ( $m^3 \times 10^9$ )	(Period III) ( $m^3 \times 10^9$ )
2007	Daily	0.29	0.25
2008		0.18	0.20

Period III, the storage release was  $0.25 \times 10^9 m^3$  (2007) and  $0.20 \times 10^9 m^3$  (2008) (Table 6). The difference between Period I and III is equal to the storage buildup or release in Period II, in a simple mass balance approach. Also, for the simulations on hourly basis, a seasonal freshwater storage occurred from approximately June through July (Period I), and a storage release from approximately end of July through August (Period III) (Fig. 5, parts c and d). For the hourly time step case, the division of the time series seems more simple (Fig. 5, parts c and d), however only indicating a storage buildup for the first half of the melting period, and storage release for the second half. The seasonal delay—the temporary storage buildup and release—of freshwater from Kangerlussuaq is typical for glacierized basins: a delay due to changes in hydrological response related to the GrIS drainage properties.

On a monthly scale, for 2007 the lag time varied over the summer season from 2 days in June to 0 days (for both daily and hourly simulations) in August (Table 7), overall indicating a decreasing lag time through the melt period. Also, for 2008 the lag time varied over the melt season from 1 day to 0 days (for both daily and hourly simulations) (Table 7). It is expected that a decrease in lag time occurred, due to both an overall more efficient internal drainage system throughout the season, and the seasonal amount of water stored and released within the system.

*COMPARISON BETWEEN 2006/2007 AND 2007/2008 SIMULATIONS*

For 2006/2007, the simulated cumulative SMP was  $1.76 \times 10^9 m^3$  based on daily time step (Fig. 3, part d; Table 4), and  $2.06 \times 10^9 m^3$  based on hourly time step (Fig. 5, part a; Table 4), averaging  $1.9 \times 10^9 m^3$  (or 310 mm w.e.). For 2007/2008, the simulated SMP was  $1.27 \times 10^9 m^3$  and  $1.38 \times 10^9 m^3$ , respectively, averaging  $1.3 \times 10^9 m^3$  (or 220 mm w.e.) (Figs. 4, part d; and 5, part b; Table 5). This indicates a reduction in simulated SMP of 30% from 2006/2007 to 2007/2008. This reduction is consistent with observed catchment runoff values. The reduction in modeled SMP of 30% from 2006/2007 to 2007/2008 appeared to follow the overall variation in the satellite-derived GrIS surface melt extent for 2007 and 2008. From 2007 to 2008, the GrIS melt extent decreased 25% (Steffen et al., 2008). Melt extent reduction in the broad GrIS perspective seemed to occur simultaneously with reduction in simulated SMP for the Kangerlussuaq drainage area.

Therefore, it is expected that the reduction in annual simulated SMP of 30% might be explained by variations in local meteorological conditions. This explanation is based on meteorological records (June through August) from Station K (the only station in the catchment where both air temperature and precipitation are observed), which show a surprisingly similar mean summer temperature for the 2 years of 10.5 °C and 10.3 °C, but a more pronounced difference in precipitation. The corrected precipitation (June through August) was 119 mm w.e. for 2007, but only 72 mm w.e. for 2008, indicates a difference of 47 mm w.e. Since Station K data was recorded at Kangerlussuaq (in the proglacial area), not on the GrIS, one must be careful about conclusively stating the reason for the 30% reduction in cumulative SMP, as there was a different climate and variability on and outside the GrIS. Obviously, it is possible that the meteorological data from Station K were not representative of the conditions on the GrIS. Therefore, a comparison between, e.g., Station S5 and Station S9 mean summer temperature for 2007 and 2008 was conducted, which showed mean summer temperatures for the two years of 4.2 °C and 3.9 °C, and of  $-0.2$  °C and  $-2.4$  °C, respectively. Due to the change (the decrease) in observed mean summer GrIS temperature at Station S5 of  $-0.3$  °C and Station S9 of  $-2.2$  °C between 2007 and 2008, the reduction in annual simulated SMP of 30% seemed to occur simultaneously with a decrease in the local GrIS summer temperature conditions. (Note: of course changes in near surface air temperature do not cause melt variations, energy fluxes do; for a discussion of interannual melt variability and its forcing at the K-transect AWS, see Van den Broeke et al., 2011).

Figures 3 (part d) and 4 (part d) illustrate the annual simulated time series for daily SMP throughout winter and summer from 2006/2007 and 2007/2008. During winter (September/October through May), the occurrence of SMP events did not happen on a daily basis (nor on hourly basis) for the Kangerlussuaq drainage area. The first day of the year in 2007 where simulated SMP occurred was 13 May (DOY 133) for both daily and hourly simulations. For 2008 it was 30 April (DOY 121) (Figs. 4, part d; and 5, part d). Visual observations indicate that outlet runoff normally starts around mid/late April, approximately 2–3 weeks before simulated SMP, and stops in late September to mid-October, which is in accordance with simulations.

In the beginning of the melt period (April and May), simulated surface melt was dominated by snowmelt, while later in the melt season (mid-July and August), when the snow cover was largely gone, simulated surface melt was controlled by GrIS glacier-ice melt. But when a snowpack was present, SnowPack calculated internal refreezing and retention when surface meltwater penetrates the snow. Not including these routines would lead to: (1) an earlier simulated SMP by up to 81 days for Kangerlussuaq; and (2) an overestimation of the simulated SMP amount to the Kangerlussuaq Fjord by up to 65%. This simulated value is below the previous values estimated for the Jakobshavn drainage area, averaging 80% (Mernild et al., 2010), and above the

**TABLE 7**

**Monthly variations in lag time between simulated SMP and observed catchment outlet runoff for the period 1 June through 31 August, 2007 and 2008 (daily and hourly time step). For each monthly interval the lag time with the highest produced  $r^2$ -value is listed.**

	2007		2008	
	Daily time step	Hourly time step	Daily time step	Hourly time step
June 1–June 30	2-day (0.68)	1-day (0.77)	1-day (0.82)	1-day (0.79)
July 1–July 31	1-day (0.82)	0-day (0.44)	0-day (0.49)	0-day (0.42)
August 1–August 31	0-day (0.76)	0-day (0.59)	0-day (0.93)	0-day (0.71)

entire GrIS of approximately 25%, estimated by Janssens and Huybrechts' (2000) single-layer snowpack model (used, e.g., by Hanna et al., 2008), and of 19–27% by Mernild et al. (2008).

### SNOWMODEL IMPROVEMENTS

SnowModel does not yet include a grid-distributed routing and temporary storage tool for the GrIS and proglacial landscape hydrology. These features clearly play important roles in controlling the flow pattern from the GrIS. Water movement in and under a glacier is intrinsically complex and not well understood, because it involves water (the liquid phase) moving through the ice (solid phase) at the melting temperature, all while the ice is sliding and deformable and allowing englacial conduits to change size and shape. To improve our SnowModel GrIS simulations, a routing model—a submodel named *HydroFlow*—will be developed to simulate, e.g., individual drainage basins, flow network, and runoff hydrographs at catchment outlets. Figure 5 (parts c and d) includes an observed short-lived jökulhlaup event in 2007 and 2008, both on 31 August. While it is clear that such observed releases of water occurred on the GrIS and certainly influenced general runoff and peak event timing and magnitudes, *HydroFlow* will unfortunately not account for such sudden releases of water storage.

### Summary and Conclusion

This study presents daily and hourly SMP simulations from a sector of the GrIS—the Kangerlussuaq drainage area—for the period 2006/2007 and 2007/2008. This simulated GrIS series yielded insights into the present conditions and the variability of SMP, lag time, and storage buildup and storage release for Kangerlussuaq. There is an acceptable degree of agreement between the simulated SMP and the observed runoff, both indicating decreasing values from 2006/2007 to 2007/2008, strongly influenced by climate conditions. Understanding the GrIS SMP, the storage buildup and storage release, and the hydrologic response (lag time) is far from complete. Thus, initial SMP simulations from Kangerlussuaq have helped to fill the gap to understand the challenges by modeling the GrIS freshwater routing (through snow, firn, and ice) and its temporary seasonal storage and release due to dynamic processes and deformation of the internal drainage system.

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### References Cited

ACIA, 2005, *Arctic Climate Impact Assessment*. Cambridge: Cambridge University Press, 1042 pp.

Allerup, P., Madsen, H., and Vejen, F., 1998: Estimating true precipitation in arctic areas. In *Proceedings Nordic Hydrolog-*

ical Conference, Helsinki, Finland. Nordic Hydrological Programme Report, 44: 1–9.

Allerup, P., Madsen, H., and Vejen, F., 2000: Correction of precipitation based on off-site weather information. *Atmospheric Research*, 53: 231–250.

Bamber, J., Ekholm, S., and Krabill, W., 2001: A new, high-resolution digital elevation model of Greenland fully validated with airborne laser altimeter data. *Journal of Geophysical Research*, 106(B4): 6733–6746.

Box, J. E., Bromwich, D. H., Vennhuis, B. A., Bai, L.-S., Stroeve, J. C., Rogers, J. C., Steffen, K., Haren, T., and Wang, S.-H., 2006: Greenland Ice Sheet surface mass balance variability (1988–2004) from calibrated Polar MM5 output. *Journal of Climate*, 19: 2783–2800.

Campbell, W. I., and Rasmussen, L. A., 1973: The production, flow and distribution of meltwater in a glacier treated as a porous medium. In *Union Geodesique et Geophysique Internationale, Association Internationale d'Hydrologie Scientifique, Commission de Neiges et Glaces, Symposium on the Hydrology of Glaciers*, Cambridge, 7–13 September 1969. *IAHS Publication*, 95: 11–27.

Dowdeswell, J. A., Hagen, J. O., Björnsson, H., Glazovsky, A. F., Harrison, W. D., Holmlund, P., Jania, J., Koerner, R. M., Lefauconnier, B., Ommanney, C. S. L., and Thomas, R. H., 1997: The mass balance of circum-arctic glaciers and recent climate change. *Quaternary Research*, 48: 1–4, no. QR971900: 1–14.

Ettema, J., van den Broeke, M., van Meijgaard, E., van de Berg, M. J., Bamber, J. L., Box, J. E., and Bales, R. C., 2009: Higher surface mass balance of the Greenland Ice Sheet revealed by high-resolution climate modeling. *Geophysical Research Letters*, 36: L12501, doi:10.1029/2009GL038110.

Fettweis, X., 2007: Reconstruction of the 1979–2006 Greenland Ice Sheet surface mass balance using the regional climate model MAR. *The Cryosphere*, 1: 21–40.

Fettweis, X., Tedesco, M., van den Broeke, M., and Ettema, J., 2011: Melting trends over the Greenland Ice Sheet (1958–2009) from spaceborne microwave data and regional climate models. *The Cryosphere*, 5: 359–375, doi:10.5194/tc-5-359-2011.

Hanna, E., Box, J., and Huybrechts, P., 2007: Greenland Ice Sheet mass balance. Arctic Report Card 2007, update to State of Arctic Report 2006, NOAA. Available at <http://www.arctic.noaa.gov/reportcard/>.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M., 2008: Increased runoff from melt from the Greenland Ice Sheet: a response to global warming. *Journal of Climate*, 21: 331–341.

Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A., and Ribergaard, M. H., 2009: Hydrologic response of the Greenland Ice Sheet: the role of oceanographic warming. *Hydrological Processes*, 23: 7–30.

IPCC, 2007: Summary for policymakers. In *Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.), Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press, p. 996.

Janssens, I., and Huybrechts, P., 2000: The treatment of meltwater retention in mass-balance parameterisation of the Greenland Ice Sheet. *Annals of Glaciology*, 31: 133–140.

Jansson, P., Hock, R., and Schneider, T., 2003: The concept of glacier storage: a review. *Journal of Hydrology*, 282: 116–129.

Johannessen, O. M., Khvorostovsky, K., Miles, M. W., and Bobylev, L. P., 2005: Recent ice sheet growth in the interior of Greenland. *Science*, 310: 1013–1016, doi:10.1126/science.1115356.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H., and Zhang, T., 2007: Observations: changes in snow, ice and frozen ground. In *Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the*

- Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press, p. 48.
- Liston, G. E., 1995: Local advection of momentum, heat, and moisture during the melt of patchy snow covers. *Journal of Applied Meteorology*, 34(7): 1705–1715.
- Liston, G. E., and Elder, K., 2006a: A distributed snow-evolution modeling system (SnowModel). *Journal of Hydrometeorology*, 7: 1259–1276.
- Liston, G. E., and Elder, K., 2006b: A meteorological distribution system for high resolution terrestrial modeling (MicroMet). *Journal of Hydrometeorology*, 7: 217–234.
- Liston, G. E., and Hall, D. K., 1995: An energy-balance model of lake-ice evolution. *Journal of Glaciology*, 41: 373–382.
- Liston, G. E., and Hiemstra, C. A., 2008: A simple data assimilation system for complex snow distributions (SnowAssim). *Journal of Hydrometeorology*, 9: 989–1004.
- Liston, G. E., and Sturm, M., 1998: A snow-transport model for complex terrain. *Journal of Glaciology*, 44: 498–516.
- Liston, G. E., and Sturm, M., 2002: Winter precipitation patterns in arctic Alaska determined from a blowing-snow model and snow-depth observations. *Journal of Hydrometeorology*, 3: 646–659.
- Liston, G. E., and Sturm, M., 2004: The role of winter sublimation in the Arctic moisture budget. *Nordic Hydrology*, 35(4): 325–334.
- Liston, G. E., Winther, J.-G., Bruland, O., Elvehøy, H., and Sand, K., 1999: Below surface ice melt on the coastal Antarctic ice sheet. *Journal of Glaciology*, 45(150): 273–285.
- Liston, G. E., Hiemstra, C. A., Elder, K., and Cline, D. W., 2008: Mesocell study area snow distributions for the Cold Land Processes Experiment (CLPX). *Journal of Hydrometeorology*, 9(5): 957–976.
- Mernild, S. H., and Hasholt, B., 2006: Climatic control on river discharge simulations, Mittivakkat Glacier catchment, Ammassalik Island, SE Greenland. *Nordic Hydrology*, 37(4–5): 327–346.
- Mernild, S. H., and Hasholt, B., 2009: Observed runoff, jökulhlaups, and suspended sediment load from the Greenland Ice Sheet at Kangerlussuaq, West Greenland, for 2007 and 2008. *Journal of Glaciology*, 55(193): 1–4.
- Mernild, S. H., and Liston, G. E., 2010: The influence of air temperature inversion on snow melt and glacier surface mass-balance simulations, SW Ammassalik Island, SE Greenland. *Journal of Applied Meteorology and Climate*, 49(1): 47–67.
- Mernild, S. H., Liston, G. E., Hasholt, B., and Knudsen, N. T., 2006a: Snow distribution and melt modeling for Mittivakkat Glacier, Ammassalik Island, SE Greenland. *Journal of Hydro-meteorology*, 7: 808–824.
- Mernild, S. H., Hasholt, B., and Liston, G. E., 2006b: Water flow through Mittivakkat Glacier, Ammassalik Island, SE Greenland. *Danish Journal of Geography*, 106(1): 25–43.
- Mernild, S. H., Liston, G. E., Hiemstra, C. A., and Steffen, K., 2008: Surface melt area and water balance modeling on the Greenland Ice Sheet 1995–2005. *Journal of Hydrometeorology*, 9(6): 1191–1211, doi:10.1175/2008JHM957.1.
- Mernild, S. H., G. E. Liston., C. A. Hiemstra., and K. Steffen., 2009a: Record 2007 Greenland Ice Sheet surface melt-extent and runoff. *Eos Transactions of the American Geophysical Union*, 90(2): 13–14.
- Mernild, S. H., Liston, G. E., Hiemstra, C. A., Steffen, K., Hanna, E., and Christensen, J. H., 2009b: Greenland Ice Sheet surface mass-balance modeling and freshwater flux for 2007, and in a 1995–2007 perspective. *Hydrological Processes*, 23: 2470–2484, doi:10.1002/hyp.7354.
- Mernild, S. H., Liston, G. E., Steffen, K., and Chylek, P., 2010: Meltwater flux and runoff modeling in the ablation area of the Jakobshavn Isbræ, West Greenland. *Journal of Glaciology*, 56(195): 20–32.
- Mernild, S. H., Mote, T., and Liston, G. E., 2011: Greenland Ice Sheet surface melt extent and trends, 1960–2010. *Journal of Glaciology*, 57(204): 621–628.
- Nick, F. M., Vieli, A., Howat, I. M., and Joughin, I., 2009: Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience*, 2(2): 110–114.
- Parizek, B. R., and Alley, R. B., 2004: Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations. *Quaternary Science Reviews*, 23: 1013–1027.
- Pimentel, S., and Flowers, G. E., 2011: A numerical study of hydrologically driven glacier dynamics and subglacial flooding. *Proceedings of the Royal Society, A*, 467: 537–558, doi:10.1098/rspa.2010.0211.
- Röthlisberger, H., and Lang, H., 1987: Glacial hydrology. In Gurnell, A. M., and Clark, M. J. (eds.), *Glacio-fluvial Sediment Transfer*. New York: Wiley, 207–284.
- Scambos, T., and Haran, T., 2002: An image-enhanced DEM of the Greenland Ice Sheet. *Annals of Glaciology*, 34: 291–298.
- Serreze, M. C., and Barry, R. G., 2005: *The Arctic Climate System*. Cambridge Atmospheric and Space Science Series. Cambridge and New York: Cambridge University Press, 424 pp.
- Steffen, K., and Box, J., 2001: Surface climatology of the Greenland Ice Sheet: Greenland climate network 1995–1999. *Journal of Geophysical Research*, 106(24): 33951–33964.
- Steffen, K., Clark, P. U., Cogley, J. G., Holland, D., Marshall, S., Rignot, E., and Thomas, R., 2008: Rapid changes in glacier and ice sheet and their impacts on sea level. In: *Abrupt Climate Change, a Report by the US Climate Change Science Program and the Subcommittee on Global Change Research*. Reston, Virginia: U.S. Geological Survey, 60–142.
- Stenborg, T., 1970: Delay of runoff from a glacier basin. *Geografiske Annaler*, 52A: 1–30.
- van de Wal, R. S. W., Greuell, W., van den Broeke, M. R., Boot, W., Snellen, H., Reijmer, C. H., and Oerlemans, J., 2005: Surface mass balance observations and AWS data along a transect near Kangerlussuaq, West-Greenland. *Annals of Glaciology*, 42: 311–316.
- van den Broeke, M., Smeets, P., Ettema, J., and Munneke, P. K., 2008a: Surface radiation balance in the ablation zone of the west Greenland Ice Sheet. *Journal of Geophysical Research*, 113: D13105, doi:10.1029/2007/JD009283.
- van den Broeke, M., Smeets, P., and Ettema, J., 2008b: Surface layer climate and turbulent exchange in the ablation zone of the West Greenland Ice Sheet. *International Journal of Climatology*, 29: 2309–2323, doi:10.1002/joc.1815.
- van den Broeke, M. R., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B., 2009: Partitioning recent Greenland mass loss. *Science*, 326: 984–986.
- van den Broeke, M. R., Smeets, C. J. P. P., and van de Wal, R. S. W., 2011: The seasonal cycle and interannual variability of surface energy balance and melt in the ablation zone of the West Greenland Ice Sheet. *The Cryosphere*, 5: 377–390.
- Yang, D., Goodison, B. E., Metcalf, J. R., Golubev, V. S., Bates, R., Pangburn, T., and Hanson, C. L., 1998: Accuracy and NWS 8 standard nonrecording precipitation gauge: results and application of WMO intercomparison. *Journal of Atmospheric Oceanic Technology*, 15: 54–68.
- Zwally, J. H., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002: Surface melt-induced acceleration of Greenland Ice-Sheet flow. *Science*, 297: 218–222.

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