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Modeling Suspended Sediment Concentration and Transport, Mittivakkat Glacier, Southeast Greenland

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Abstract

Suspended sediment concentration and transport is modeled for the Mittivakkat Glacier located on Ammassalik Island, South-East Greenland, using a numerical sediment model based on lumped-elements. Empirical equations calculate sediment erosion and deposition within a constant idealized glacier drainage system. The sediment model is forced by observations and an energy balance model based on meteorological observations that provide a 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) from the glacier surface which is available for subglacial erosion, glaciofluvial transport, and deposition within the drainage system. The idealized drainage system is constrained following the descriptions and conclusions from previous work. A model simulation run for summer 2005 shows that the cumulative modeled suspended sediment transport lies within 3% when compared with observations. Model results show that the temporal changes in the calculated suspended sediment concentrations vary over the melt season in some agreement with measured field data for the summer of 2005. Forcing the sediment model gives a correlation coefficient of 0.89 using observed proglacial meltwater discharge values and the correlation coefficient is 0.63 using modeled supraglacial meltwater runoff. The sediment model successfully captures the observed concentration and transport of suspended sediment which indicates a sufficient sediment reservoir available for transport through the idealized drainage system.

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Introduction

Suspended sediment is present in glacial meltwater runoff and glaciated catchments, varying from small amounts to high concentrations depending on glacier location, size, bedrock characteristics, and climatic conditions (Hasholt et al., 2006; Bartholomew et al., 2011). In recent years glaciological investigations have turned more towards a better understanding of basal processes and the feedback on glacier behavior from a perspective of changing climate (Bartholomaus et al., 2008; Bartholomew et al., 2010; Schoof, 2010). This is not only driven by the need to understand the processes of sediment production, but also because the climate impact on glacier mass balance does influence the dynamics of a glacier and its coupling to the bed (Sundal et al., 2011). The transport of sediment from glaciated areas significantly influences the downstream natural fluvial system, determining the degree of braiding and the development of deltas in lakes and fjords (Hasholt and Mernild, 2008). The transport of sediment from a glacier into a fjord is under influence of climate changes which can be coupled to the activity of the glacier system (McGrath et al., 2010; Andresen et al., 2012).

Fluvial transport of sediments is the major mechanism operating outside the glaciers to export substantial amounts of material from glaciated catchments towards the ocean, rendering measurements of sediment transport in proglacial rivers of central interest (Mernild and Hasholt, 2009). Direct measurements of suspended sediment transport are difficult, expensive, and time consuming, especially in the Arctic and Greenland (McDonald et al., 2010). Therefore the application of models capable of reproducing the output of sediment from a glaciated area is a valuable contribution to the study of glacial landforms (Hasholt et al., 2008). The Mittivakkat Glacier located on Ammassalik Island in Southeast Greenland and the associated local precipitation pattern can be perceived as a typical Arctic landscape system with its own water and sediment cycle that connects to the Sermilik Fjord (Mernild et al., 2010). To model sediment movement through a subglacial hydrological system, detailed knowledge of meltwater movement through the glacier is needed in order to understand the source, characteristics, and availability of the sediment being transported, and physical processes involved in entraining, transporting, and depositing the sediment (Hasholt and Mernild, 2008; Bartholomew et al., 2011). Modeling and understanding the influence of climate change on ice/bed coupling and its consequences on sediment production require a set of rather dense input data in space and time and a numerical model which is able to represent the physical conditions at the glacier bed. At present these types of models are few and biased by an insufficient development of the theoretical framework (e.g. Hildes et al., 2004; Schoof, 2010; Herman et al., 2011). Comprehensive and detailed models are, for example, still widely based on empirical relationships in the physics of erosion rates, subglacial water pressure, and the timing of switching from a distributed to a channelized subglacial water flow, which require some degree of tuning to match observations. Moreover, observations of Arctic subglacial conditions are even fewer, justifying the use of different, simple, and alternative approaches to describe the transport of glacial sediment in Arctic environments (Alley et al., 1997; Fischer and Clarke, 2001; Clarke, 2005; Bartholomew et al., 2011). Furthermore, to understand the recent inter-annual suspended sediment variability would be valuable information for future climate scenario runs of the glacier system.

This study deals with a numerical model of the glaciofluvial erosion and transport of suspended sediment forced with an energy balance model and proglacial discharge observations. The sediment model uses the lumped element approach developed by Clarke (1996a, 1996b) for the specific catchment of the Mittivakkat Glacier for the period September 2003 through August 2006 (Fig. 1). The modeled suspended sediment concentration is then compared to proglacial observations by the hydrometric station from the study by Hasholt and Mernild (2006) in order to assess and evaluate the amount of suspended sediment that comes from the glacier. The conduit system is spatially constrained following the conclusions from Mernild (2006) and Mernild et al. (2006). The sediment model is forced by a physically based energy balance model and snow model (SnowModel) described in Mernild et al. (2008) that provide a simulated Surface Melt and liquid Precipitation available for supra-, en-, sub-, and proglacial flow processes after vertical percolation and potential storage within the snowpack (SMP) over the glacier which is available for drainage. The modeling of suspended sediment transport forced with an energy balance model is a new approach to quantify the seasonal and inter-annual variation of sediment transport to the catchment area for periods with no observations for this glacier system.

Study Area and Previous Observations

The Mittivakkat Glacier is located on Ammassalik Island, Southeast Greenland (Fig. 1), and is subject to a maritime climate with a relatively small annual temperature range and high precipitation rates (around 2 m yr^{-1}). The mean annual air temperature for the whole catchment area including the glacier is -1.7 ± 0.3 °C with the equilibrium elevation altitude around 730 m. Mittivakkat Glacier has a long history of scientific investigation dating back to the 1930s, and since 1933 it has shown a gradual retreat of the glacier front indicating a volume decrease of more than 10% since mid-1990s (Mernild et al., 2011).

Hasholt and Mernild (2006) presented results from their monitoring efforts on suspended sediment concentration and transport at automated stations located near the outlet from the Mittivakkat Glacier to get an estimate of the glaciofluvial erosion available for transportation from the glacier terminus. Due to the inherent difficulties associated with measuring suspended sediment, Hasholt and Mernild (2006) employed three independent methods. The automatic station used two different sensors to measure the suspended sediment concentration, namely a Partech IR 500 infrared transmissometer and an optical backscatter probe (OBS), where the third was a rating curve method. The rating curve method is based on a linear fit between suspended sediment concentration measured in manually collected water samples (typically 4 times a day) and the observed water discharge. The temporal resolution of the recording was set to 10 min for a 60 d (day of year [DOY] 161–220) period during the summer of 2005. Hasholt and Mernild (2006) gave a detailed description on how the sensors were installed and calibrated, and on how the data were collected. The accuracy of the observed water discharge and suspended sediment concentration is within $\pm 7\%$ and $\pm 5\%$, respectively (Hasholt and Mernild, 2006). Hasholt and Mernild (2006) described the Partech IR 500 infrared transmissometer as the most robust sensor, which is less sensitive to tilt when compared to the OBS probe. The OBS probe had tilted on 26 June until it was corrected on 28 July, which resulted in a larger uncertainty on the OBS sensor record for that period. Based on this, the Partech data set was chosen to compare with the results from the sediment model.

Model Description

WATER TRANSPORT

Clarke (1996a) introduced several idealized hydraulic-circuit elements to describe water discharge formulations through a glacier that include suspended sediment transport. Subglacial drainage systems may consist of numerous individual and highly dynamic conduits which eventually end up in a few large subglacial tunnels that transport the meltwater to the glacier terminus. The conduits will be more dynamic under thicker ice and can close in time scales of days for decreasing water input if the ice is thick enough (Fountain and Walder, 1998; Bartholomaus et al., 2008).

The configuration of the subglacial hydrological system used in this study follows the work by Clarke (1996b), and the various drainage paths of the idealized conduit system are sketched in Figure 2. The subglacial hydrological system consists of three different elements draining the water through the system. All the elements are constant in size and constrained by observations from Mernild (2006). First is the crevasse feeder (CF), which is thought of as an ideal discharge and storage volume that effectively leads the water from the surface down to the bedrock. A subglacial channel (SGC-1) will then transport the water and suspended sediment toward a subglacial storage volume (SSV) at the glacier bed. The water and suspended sediment then continues into the last part of the subglacial channel (SGC-2) system that ends at the glacier terminus (Clarke, 1996b).

The formation of water (SMP) from the glacier surface that enters the hydraulic system is modeled using an energy balance and snow and ice model (SnowModel). SnowModel also contains a physically based snow-evolution modeling component employing various snow accumulation and redistribution schemes, to describe the variations in the surface melt of snow and glacier ice, snow accumulation, and temperature, density, and variable surface albedo of the snow over the whole Mittivakkat Glacier. The combined model is fully described elsewhere and summarized briefly below (Liston and Elder, 2006a, 2006b; Mernild et al., 2010).

SnowModel is a spatially distributed system for modeling meteorological conditions, snow-evolution, snow and ice melting, and surface runoff given meteorological forcing. It simulates surface energy and moisture exchanges, including snow and glacier melt, multi-layer heat- and mass-transfer processes in snow (e.g., snowpack temperature and density evolution). SnowModel routines have been described and tested in the Arctic, e.g. (Liston and Elder, 2006a, 2006b; Mernild et al., 2010). SnowModel is composed of four submodels: MicroMet defines the meteorological forcing conditions (Liston and Elder, 2006b); EnBal calculates the surface energy exchanges (Liston, 1995); SnowPack simulates mass and heat transfer processes due to, for example, retention and internal refreezing (not including retention/refreezing routines in SnowModel would lead to an overestimation of runoff to the ocean [Liston and Hall, 1995]); SnowTran-3D is a blowing-snow model that ac-

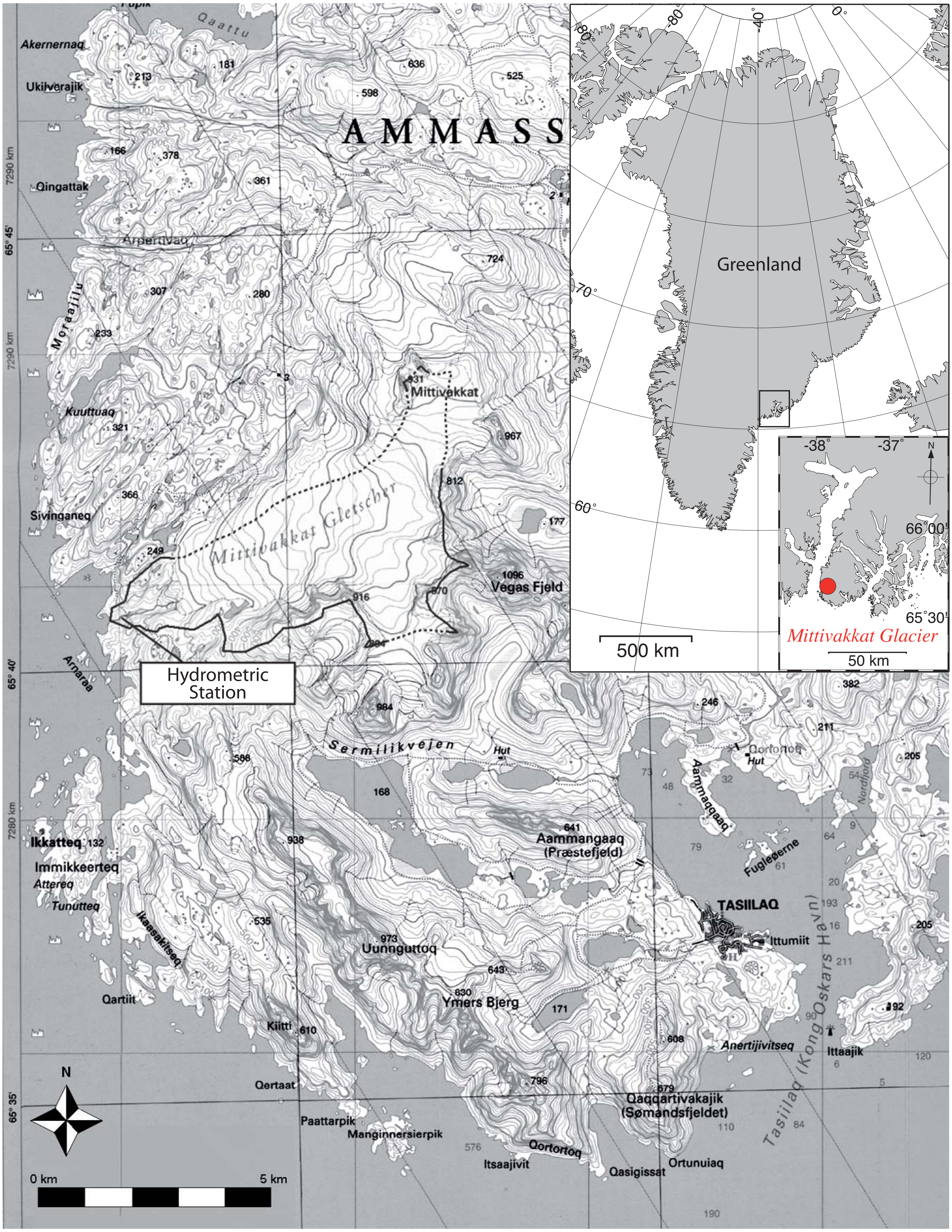

FIGURE 1. Map of Greenland showing the location of the Mittivakkat Glacier, the hydrometric station described in Hasholt and Mernild (2006), and the catchment watershed divide after Mernild et al. (2008) (modified after Greenland Tourism).

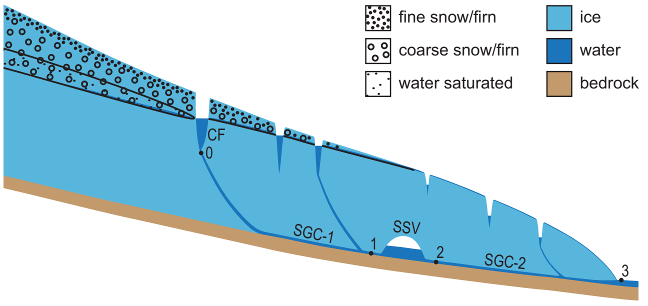

FIGURE 2. Schematic diagram of supraglacial, englacial, and subglacial drainage passageways. The figure is modified from Röthlisberger and Lang (1987) to sketch the conceptual elements of the model by Clarke (1996b). The circuit numbers 0, 1, 2, 3 denote places where the hydraulic head, water discharge, and suspended sediment concentrations are evaluated.

counts for snow redistribution (Liston and Sturm, 2002). Atmospheric forcing required by SnowModel is provided by MicroMet (Liston and Elder, 2006b), which assimilates and interpolates time series of air temperature, relative humidity, wind speed and direction, and precipitation from surface meteorological stations near or within the simulation domain. MicroMet uses known relationships between meteorological variables and the surrounding landscape (e.g., topography and surface characteristics) to distribute these variables in physically plausible and computationally efficient ways. Data are interpolated horizontally to a regular grid using a Barnes objective analysis scheme, which applies a Gaussian distance-dependent weighting function (Barnes, 1964; Koch et al., 1983). Interpolation weights are determined objectively as a function of data spacing and distribution. At each time step, air temperature, solar radiation, albedo, outgoing longwave radiation, latent heat flux, sensible heat flux, snowmelt, sublimation, snowmelt runoff, snow depth, and snow water equivalent are calculated and made accessible to SnowModel.

The SnowModel setup for the Mittivakkat Glacier is presented in Mernild et al. (2006) and the data are provided with a daily temporal resolution for a 3-year period (September 2003 through August 2006). All calculated SMP from SnowModel limited by the catchment watershed divide introduced by Mernild et al. (2008) is assumed to enter the drainage system. The traveling times were estimated for the whole glacier represented by average travel times for eight 100-m-elevation intervals. The traveling time was found to be approximately 0–13 h depending on elevation before it reached the terminus (Mernild, 2006). The implication of this result for the sediment model is that all the modeled meltwater runoff is forced to run through the conduit system the same day, which justifies the use of daily time-step simulation. The digital elevation and bedrock models from Knudsen and Hasholt (1999) are used to define the base area from which the modeled meltwater runoff from SnowModel can access the sediment model.

SEDIMENT TRANSPORT

Modeling sediment entrainment, transport, and deposition in an idealized glacier drainage system is done following the work by Clarke (1996b). The description of erosion rate of sediment from the conduit bed relates the sediment flux from the bed suspension to the porosity of the bed, sediment density, and the bed shear stress. Values calculated for each conduit segment are carried down-glacier into the next conduit so that the sediment output for one segment forms the input for the next. The model calculates these values with a daily time-step.

The amount of eroded sediment available for suspension, which is assumed to come from an inexhaustible source, is calculated for a permeable sediment substrate having porosity n and solid-phase density ρ_s. The mass flux of sediment (F_e) from the glacier bed into fluid suspension is calculated in following way:

$$F_e = \rho_s(1 - n)k_E(\tau_0 - \tau^*)^N, \tag{1}$$

where ρ_s is the density of the sediment, n is the porosity of the sediment bed, k_E is the erosion rate constant, τ^* is the threshold stress for bed erosion, τ_0 is the shear stress of the conduit walls including the bed, and N is a constant. The shear stress at the bed is related to the stream velocity within the subglacial conduits in the following way:

$$\tau_0 = \frac{1}{8} f\rho_w v^2, \tag{2}$$

where $f = 0.25$ is the Darcy-Weisbach coefficient, ρ_w is the density of water, and $v = Q/S$ is the cross-sectionally averaged velocity of the water in a conduit with the cross section S. It is assumed that the sedimentation rate of suspended sediment is governed by Stoke's Law in the following way:

$$v_s = \frac{(\rho_s - \rho_w)gD_p^2}{18\mu}, \tag{3}$$

where v_s is the settling velocity of spherical grains with the diameter D_p, and density ρ_s within a fluid of viscosity μ and density ρ_w. The flux of sedimentation (F_s) is then given as:

$$F_S = c_s v_s = c_s \frac{(\rho_s - \rho_w)gD_p^2}{18\mu}, \tag{4}$$

where c_s is the concentration of suspended sediment. A description and value of the parameters used in Equations (1), (2), (3), and (4) are given in Table 1.

The conservation of mass (M) in the idealized hydrological conduit system relates to the changes in mass of the suspended sediment concentrations to the suspended sediment concentration input flux (F_{in}) and output flux (F_{out}) together with sediment erosion (F_e) and deposition (F_s) over time:

TABLE 1

Physical constants for the Mittivakkat glacier setup.

Property	Value
Water density, ρ_w	1000 kg·m^{-3}
Sediment density, ρ_s	2700 kg·m^{-3}
Gravity acceleration, g	9.82 m·s^{-2}
Viscosity of water, μ	1.787 × 10^{-3} Pa·s
Sediment particle diameter, D_p	7.8 × 10^{-4} m
Porosity of sediment load, n	0.35
Threshold stress for erosion, τ^*	0 Pa
Exponent for erosion law, N	1.5
Erosion rate constant, k_E	5 × 10^{-9} m·s^{-1}·Pa^{-N}

$$\frac{dM}{dt} = F_{in} + F_{out} + F_e + F_s, \quad (5)$$

where M is the mass of the sediment. The mass is substituted for the actual suspended sediment concentration (c_s) and it is assumed that the volume V of the conduit system remains constant with time in order to simplify the system of equations and their numerical solutions (Clarke, 1996b). The final suspended sediment balance is then:

$$\frac{dc_s}{dt} = \frac{1}{V[c_s^{in}Q^{in} - c_s^{out}Q^{\text{out}} + A(F_e - F_s)]}, \quad (6)$$

where Q is the water discharge and A is the bottom area of the rectangular conduits.

SIMULATION SETUP

The model for the suspended sediment is identical the setup from Clarke (1996b). It is summarized briefly below, and Figure 2 gives a visual presentation of all the elements in the combined idealized drainage system and transport of suspended sediment concentration. The observed discharge from the glacier terminus (Model A) and the SMP from SnowModel (Model B) give the input forcing to the water drainage system and suspended sediment model. The model framework can be seen in Figure 2, where the schematics show the different elements of the idealized exchange of suspended sediment and water discharge. The circuit numbers 0, 1, 2, 3 denote places in the idealized drainage system where the hydraulic head, water discharge, and suspended sediment concentration are evaluated (Clarke, 1996b). The values calculated for each segment in the conduit system are carried down the glacier in a continuous way meaning that (F_{out}, Q_{out}) for one segment of the conduit contributes (F_{in}, Q_{in}) for the next segment in line. For a detailed description of equations for each circuit numbers the reader is referred to Clarke (1996b).

Clarke (1996b) suggested parameter values to obtain suspended sediment concentration estimates for the empirical equations that calculate sediment erosion and deposition within an idealized glacier drainage system. However, the work by Mernild (2006) and Mernild et al. (2006) described and reported on the positions of the moulins and crevasses in the lower part of the ablation zone of the glacier together with a description of a more general water flow from the whole glacier for a full summer season. The lower part consists of two major conduits with slightly different traveling time. These two conduits combine to a single major conduit c. 500 m from the ice margin where it exits through a glacier portal. The majority of the surface meltwater that ends up in the subglacial conduits is thus channeled out through the glacier portal. All the parameters in Table 2 were chosen in order to meet these descriptions and constrain the size and spatial extension of the conduit system when it was possible. The rest was chosen so that the observations of suspended sediment concentration and transport for the summer season of 2005 matched reasonably well. The parameters in Table 2 describe the geometry of rectangular conduits with the dimensions l (length), w (width), and d (height). It follows, that a base area is calculated as $A = w \times l$, a cross-sectional area is calculated as $S = w \times d$, and a perimeter of a conduit is calculated as $P = 2(w + d)$. The suspended sediment concentration that leaves the glacier at the terminus is calculated with a temporal resolution of one day. The height of the crevasse feeder (h_R) was chosen based on the mean thickness of the whole glacier which was approximately 115 m in 1994. The mean thickness is calculated from the digital elevation and bedrock models described in Knudsen and Hasholt (1999). Descriptions and parameter values are provided in Tables 1 and 2.

TABLE 2

Parameters used in the sediment model for the Mittivakkat glacier. The parameters are slightly modified from Clarke (1996b) (following the descriptions in Mernild [2006] and Mernild et al. [2006]) to fit the Mittivakkat glacier.

Circuit element	Property	Value
CF	Maximum height, h_R	115 m
	Base area, A_R	10000 m^2
SGC-1	Length, l_1	3500 m
	Width, w_1	50 m
	Height, d_1	0.1 m
	Cross section, $S_1 = d_1 \cdot w_1$	5 m^2
	Friction coefficient, f_1	0.25
SSV	Maximum height, h_V	10 m
	Base area, A_V	100 m^2
SGC-2	Length, l_2	500 m
	Width, w_2	50 m
	Height, d_2	1.0 m
	Cross section, $S_2 = d_2 \cdot w_2$	50 m^2
	Friction coefficient, f_2	0.25

The modeled suspended sediment concentrations for the summer period of 2005 are compared with observed values from the study by Hasholt and Mernild (2006). The sediment model is forced with two different setups (Model A and Model B). Model A uses the proglacial observed meltwater discharge from Hasholt and Mernild (2006), and Model B uses the SMP from SnowModel, which is available for the sediment model.

Results

VARIATION OF MODEL PARAMETERS

Clarke (1996a, 1996b) suggested a wide range of parameters for different applications of the sediment model in order to demonstrate the potential of the model approach. The sediment model is able to follow the general variation but it is limited by the input values from SnowModel and the simple representation of the suspended sediment transport and drainage system. The simple representation for the sediment and drainage system has a number of empirical constants and parameterizations associated, which emphasize the need of some investigation. The selections of parameters for the variation study are chosen based on a wide range of parameter values found in the literature (Clarke, 1996a, 1996b; Jones and Arnold, 1999). The variation of model parameters was tested for the summer period of 2005 using four different values for one parameter while keeping the others constant with values from Tables 1 and 2. The model parameters are k_E, N, D_p, and S_2. The results for each parameter are then compared in order to determine the range of solutions for the model.

Jones and Arnold (1999) did a modeling study of the Haut Glacier d'Arolla in Switzerland following similar principles and

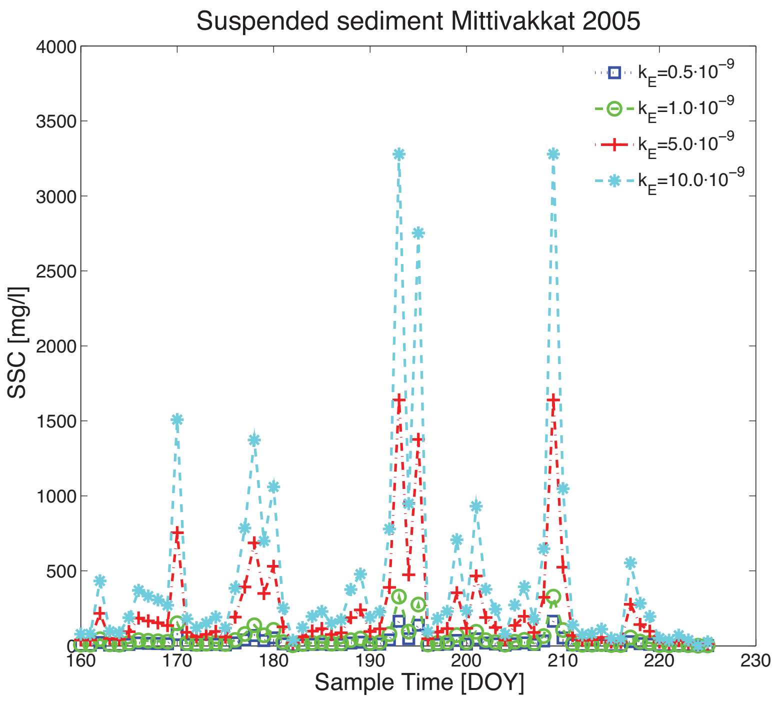

FIGURE 3. Suspended sediment concentration (SSC) from the sediment model using four different values of k_E (Table 1).

an equation setup as described in Clarke (1996b). The production of suspended sediment increases linearly with larger values of k_E and vice versa [Equation (1)] (Clarke, 1996b; Jones and Arnold, 1999). Figure 3 shows the variation in the model results based on four different values of the erosion rate constant (k_E), and it can be seen that higher values of k_E result in an overall larger production of suspended sediment in the model.

The exponent for the erosion law (N) is determined from experiments, and it controls the difference between the minimum and maximum values of the suspended sediment concentration leaving the glacier during meltwater runoff. Small and large values of N give small and large differences between the minimum and maximum values through the period due to the power law formulation in Equation (1). Increasing N also increases the overall amount of suspended sediment leaving the glacier. Jones and Arnold (1999) found that values for $N > 1.6$ gave the largest increases in the amount of suspended sediment produced. The value for N in the literature ranges from 1 to 3 depending on the bed type and the resistance of the bed to erosion (Clarke, 1996b; Alley et al., 1997; Jones and Arnold, 1999). Figure 4 shows the model variation based on

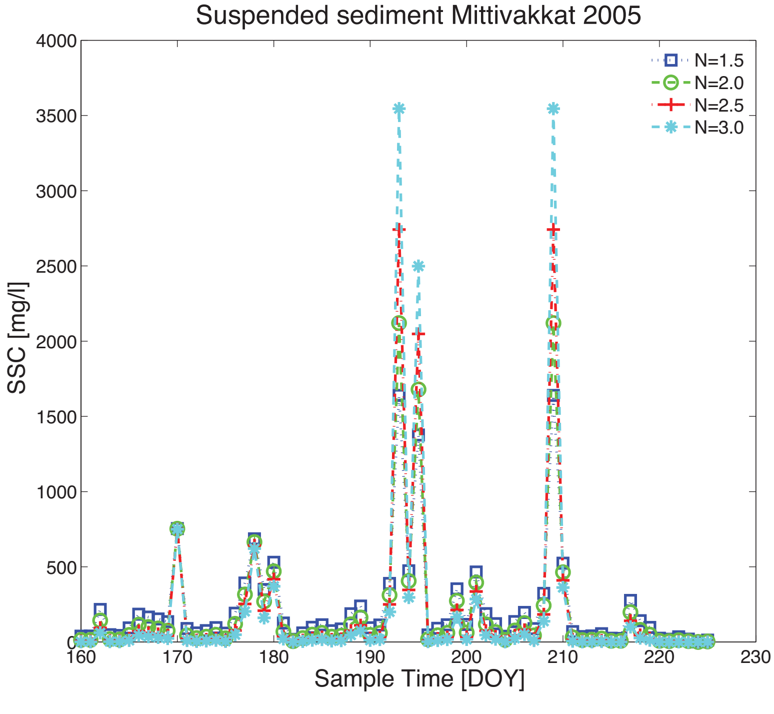

FIGURE 4. Suspended sediment concentration (SSC) from the sediment model using four different values of N (Table 1).

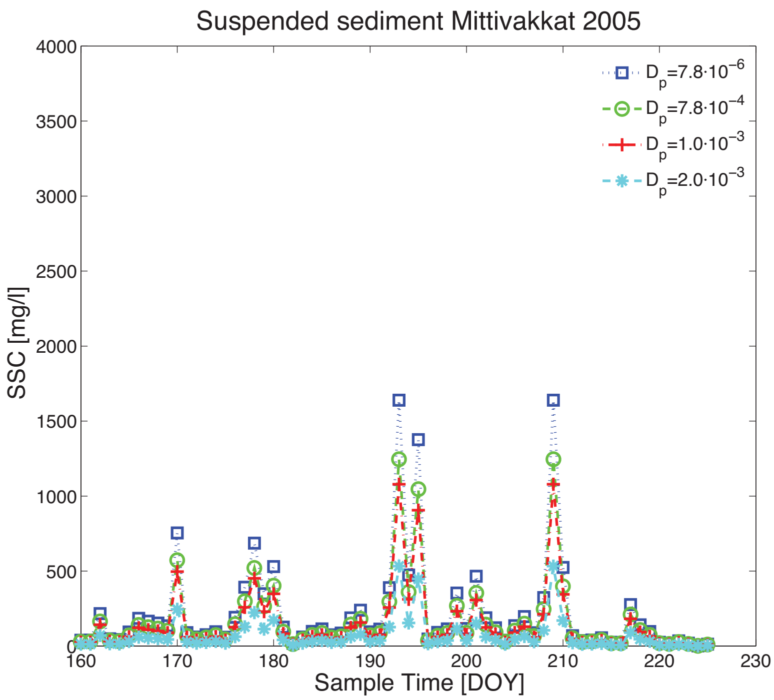

FIGURE 5. Suspended sediment concentration (SSC) from the sediment model using four different values of D_p (Table 1).

four different values of the exponent of the erosion law (*N*), and it can be seen that the difference between the minimum and maximum values increase with an increasing value of *N*.

The sedimentation rate [Equation (3)] of suspended sediment governed by Stoke's Law depends on the diameter of the suspended sediment (D_p) and has a constant value based on Clarke (1996b). Figure 5 shows the variation in the model based on four different diameters of the suspended sediment and it can be seen that the sedimentation rate increases with an increasing value of D_p and vice versa. The sedimentation of the suspended sediment is increased markedly when the diameter is larger than 1 mm. The specific value for D_p in the area of the Mittivakkat catchment was investigated and reported to range between 0.52 to 1.83 mm as described in Hasholt (1976).

The geometry of the sediment model is defined by the geometrical parameters listed in Table 2. The cross-sectional areas (*S*) of the channels are represented in the formulations of the shear stress (τ_0). The calculated suspended sediment is sensitive to changes in the cross-sectional area, and Figure 6 shows an example of the sensitivity for four different cross-sectional areas during the

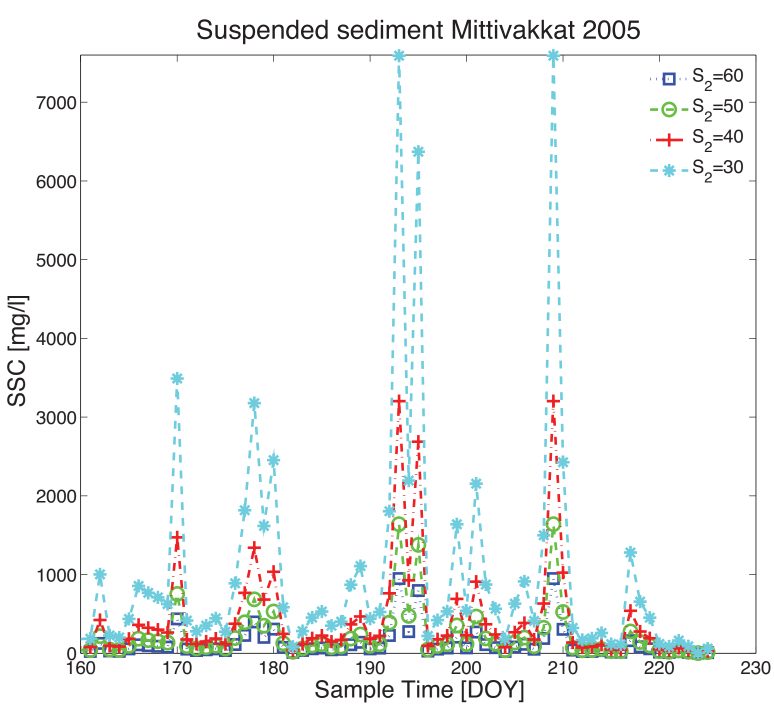

FIGURE 6. Suspended sediment concentration (SSC) from the sediment model using four different cross sections of the lower conduit system (Table 2).

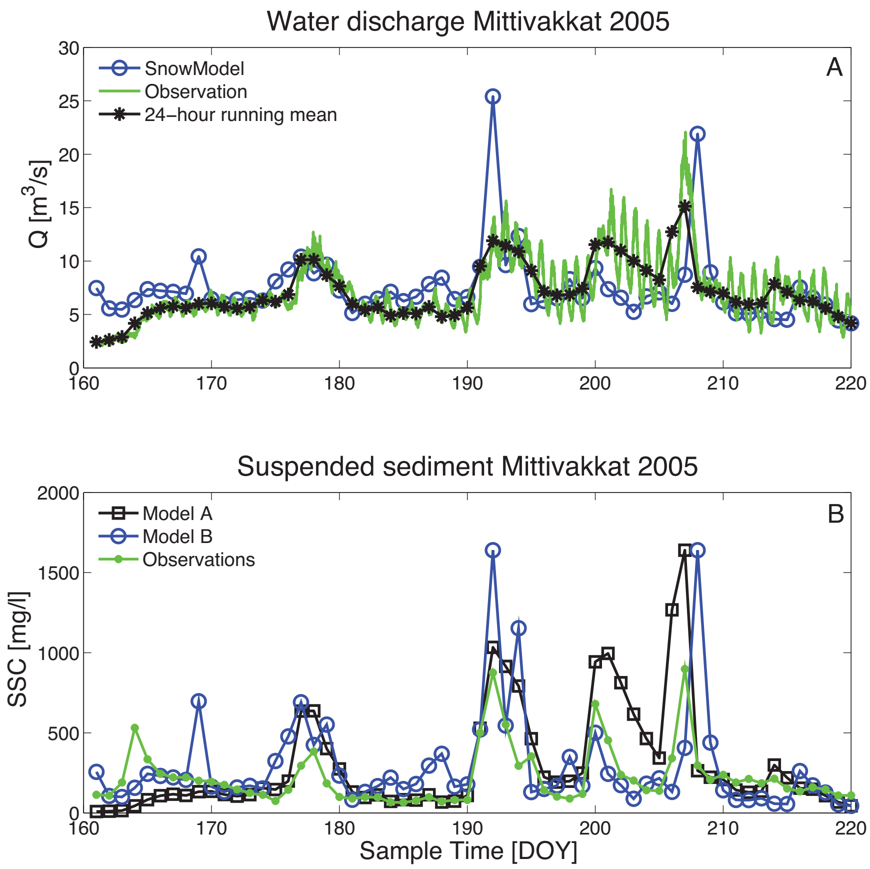

FIGURE 7. (A) Snowpack (SMP) from SnowModel and observations. Curve connecting asterisks is the calculated mean daily value of the observations. (B) Suspended sediment concentration (SSC) from the sediment model and observations.

period where observations are available. The suspended sediment concentration increases with a smaller cross-sectional area due to higher shear stress because the amount of water coming through the system is the same. The concentration of the suspended sediment will give unrealistically high values, if the cross-sectional areas are made too small.

MODEL SIMULATIONS

Figure 7, part A, shows the observed water discharge for the summer of 2005 together with the modeled daily SMP values from SnowModel. The correlation between the SMP available to the sediment model (SnowModel) and the observed mean daily values yields a correlation coefficient of 0.46 (Table 3). The SMP values from SnowModel are unable to resolve all the peaks and lows when compared to the observations. SnowModel calculates the SMP value at day 194 to be around 25 $m^3 s^{-1}$. The observations do not show a similar peak in the water discharge time series. Figure 8, part A, shows that SnowModel calculation of the input to the glacier generally is greater than the measured amount of water that leaves the glacier system in the beginning of the runoff period, which is most likely due to a limited representation of the temporal storage buildup and release in the in the glacier system (Stenborg, 1970). Apart from seasonal discrepancies in the modeled amount of SMP and observation, the modeled cumulative water discharge of $Q_{mod} = 3.93 \cdot 10^7$ m^3 and the observed value of $Q_{obs} = 3.96 \cdot 10^7$ m^3 during the summer of 2005 yields a relative difference of 0.8%.

To analyze the temporal variation of the water discharge more closely during the ablation season, the modeled and observed water discharge is compared in three different periods. The first period (DOY 161–180) represents the early ablation season where the whole glacier is still covered with snow and the hydrological drainage system is starting to develop. The second period (DOY 181–200) represents the mid ablation season where the hydrological drainage system is not fully developed yet with most snow in the lower ablation area melted away. The third period (DOY 201–220) represents the late ablation season where the hydrological drainage system is fully developed with most of the winter snow melted away. The correlation coefficients for the three periods between SnowModel and observation are listed in Table 3. The correlation coefficients indicate that the performance of Model B gets better with the development of the hydrological drainage system, simply because englacial buildup/release is not part of the

TABLE 3

Correlation coefficients for the model setup given in Tables 1 and 2 compared to observed mean daily (Model A) and mean daily SnowModel values (Model B).

Date	Setup	Model A		Model B	
		Q	c_s	Q	c_s
10 June–29 June	Period 1	1.00	0.78	0.48	0.40
30 June–19 July	Period 2	1.00	0.95	0.34	0.46
20 July–8 August	Period 3	1.00	0.88	0.71	0.93
10 June–8 August	Full period	1.00	0.89	0.46	0.63

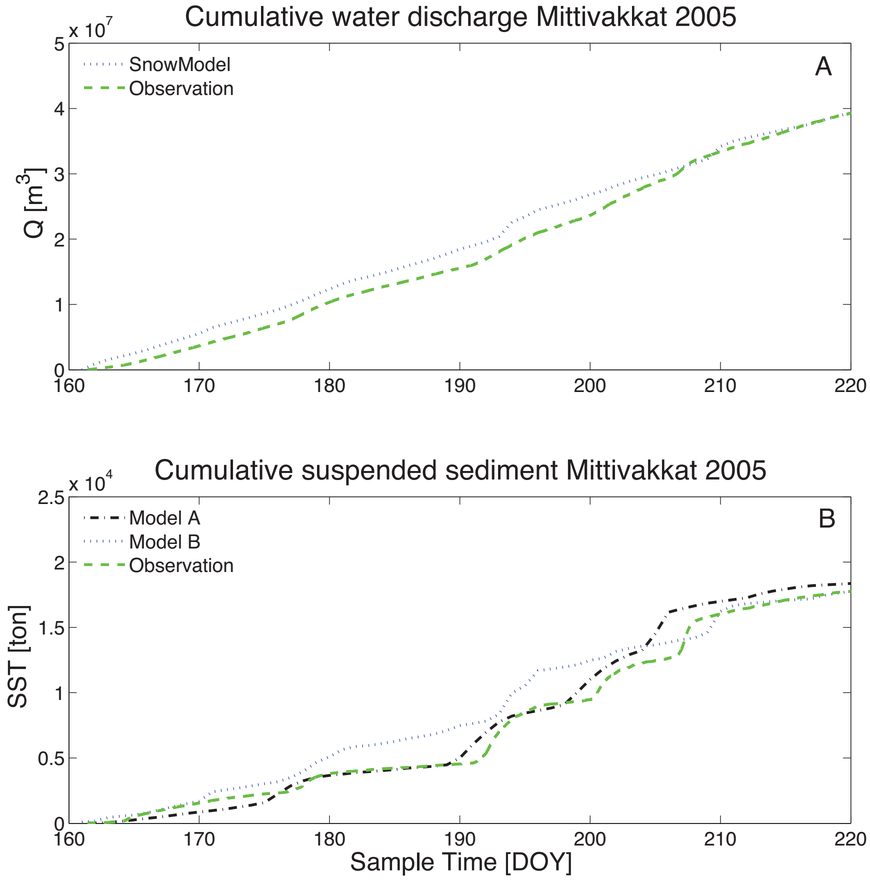

FIGURE 8. (A) Cumulative SMP from SnowModel and observations, and (B) cumulative suspended sediment transport (SST) from the sediment model and observations.

SnowModel routines. The melting of the winter snow cover and the re-establishment of the fully developed system of conduits give a better modeled timing for large melt events and the subsequent suspended sediment concentrations within the subglacial conduit system. Water velocities in the channels vary widely on a diurnal to seasonal time scale and in the conduit system on the lower part of the glacier play an important role in how much and how fast the water, and with that the suspended sediment, is transported through the system. The highest water velocities are found in the large subglacial channels in the lower part of the glacier (Mernild, 2006; Mernild et al., 2006).

The modeled suspended sediment concentration (Model run A, Table 3) using the observed proglacial discharge measurements is compared with the observed suspended sediment data collected during the melt season of 2005 from DOY 161 to 220. A comparison of the calculated mean daily observations and the sediment model output is shown in Figure 7, part B (Model run A). Observation has a correlation of 0.89 with the sediment model for the full period (Table 3 [Model A]). Looking at the before-mentioned periods in the ablation season it is likely that the same errors and uncertainties described above also hold for the suspended sediment concentration and transport because of their direct link to the input water used in the sediment model. The high correlation between observation and Model A for all three periods suggest that the simple sediment model performs well when the input water is controlled by observed water discharge, because the observed proglacial runoff has been influenced by the englacial/subglacial and storage buildup and release processes.

A comparison between the sediment model output forced with SnowModel and observation is also shown in Figure 7, part B (Model B). Observation has a correlation of 0.63 with the sediment model for the full period (Table 3 [Model B]). In general, the low correlation coefficients for the suspended sediment concentrations are not that surprising due to the link between the water discharge values (Table 3). The reason for this is that the sediment model formulates a simple, but a highly correlative, connection between the water available for drainage and the suspended sediment concentration as discussed by Hasholt and Mernild (2006). Looking again at the previously discussed periods in the ablation season it is also likely that the same errors and uncertainties described above hold for the suspended sediment concentration and transport. The correlation between observation and Model B for all three periods follow the same pattern as seen with the water discharge comparison (Model A), which suggest that Model B is limited by the same errors and uncertainties.

Figure 8, part B, shows the cumulative suspended sediment transport from the curves in Figure 7, part B. The total suspended sediment transport (SST) during the summer of 2005 for the models are SST_{ModA} = 18,358 ton and SST_{ModB} = 17,745 ton, whereas the SST from observation amounts to SST_{obs} = 17,808 ton. The relative differences between observation and the two model runs are 3.0%, relative to Model run A, and 0.4%, relative to Model run B.

In order to test the sediment model for periods with no observations, SnowModel is used as input, and Figure 9 shows a sample run on a daily time-step using the parameter set in Tables 1 and 2

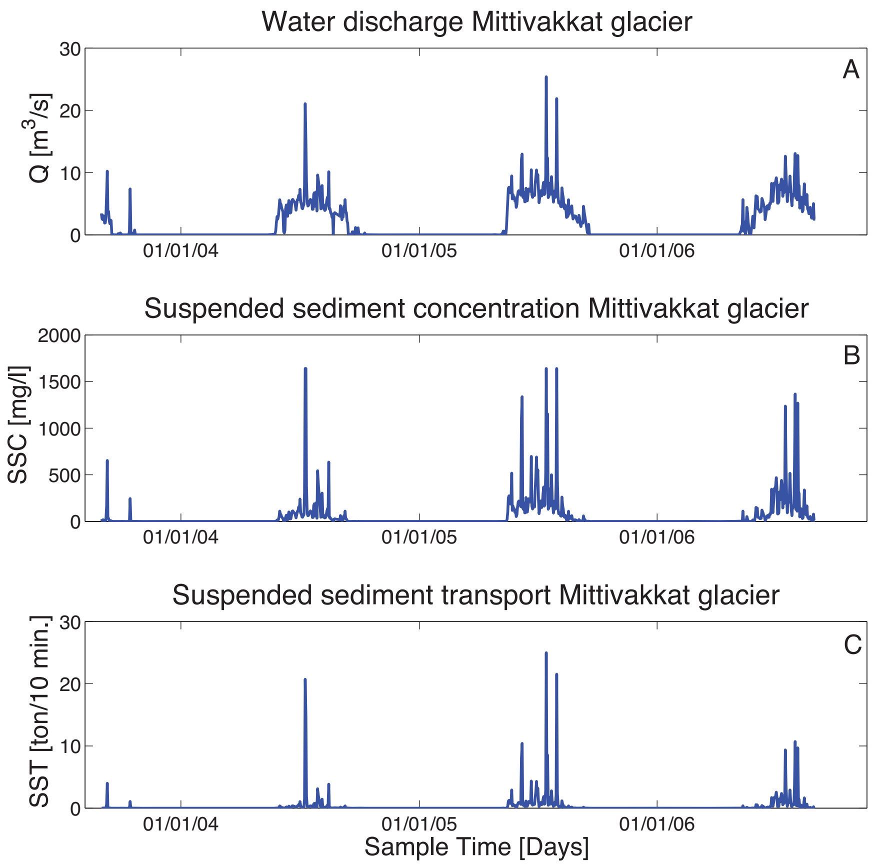

FIGURE 9. (A) Water discharge (Q) calculated from the SnowModel. (B) Suspended sediment concentration (SSC) calculated from the sediment model. (C) Suspended sediment transport (SST) calculated from the sediment model.

for a 3-year period (September 2003 through August 2006). The sample run shows the model output of water discharge (Fig. 9, part A), the suspended sediment concentration (Fig. 9, part B), and the amount of suspended sediment that is transported from the glacier terminus (Fig. 9, part C). The variations in the water discharge and the suspended sediment concentration are strongly correlated due to the simple model setup and the idealized drainage representation. The sample run clearly shows that the sediment model can be calibrated to local glaciers in Greenland and be used to produce suspended sediment concentration and transport estimates for time periods with no observation.

To test the assumption of an infinite reservoir of sediments available for suspension, the observed suspended sediment record was compared for two different periods with a similar water discharge. The first period was 4 days (DOY 179–183) at the beginning of the season, and the other was 4 days (DOY 214–218) late in the season. The two periods had a mean water discharge value of 6.9 $m^3 s^{-1}$, which corresponds to a mean suspended sediment concentrations of 117 mg L^{-1} for the early period and 164 mg L^{-1} for the late period. The difference between the two mean suspended sediment concentrations supports the assumption of an infinite reservoir of sediment available for suspension because the suspended sediment concentration for the late period is close to and slightly higher than the earlier value for the same water discharge values.

Discussion

The SMP from SnowModel does not capture all the large water discharge events observed by Hasholt and Mernild (2006). SnowModel captures the general trends in the winter, summer, and net mass balance for the period 2003–2006. However, SnowModel is unable to capture the temporal variability in runoff from the glacier during the ablation season, which introduces some errors and limitations for the input to the sediment model (Fig. 7). Early in the ablation season (period 1, DOY 161–180), these limitations could center around the evolution and the physics of a melting snowpack that may trap water in the pore space by capillary forces or as ice lenses and superimposed ice due to a large cold content (Colbeck, 1976; Pfeffer et al., 1991). SnowModel treats all of these issues as parameterizations that simplifies the physics behind the processes, but the most likely source for errors is due to an omitted model representation of the englacial/subglacial storage buildup and release of SMP in the drainage system associated with SnowModel. In the middle of the ablation season (period 2, DOY 181–200) the limitation could be due to a simplified drainage system that does not account for all the subglacial storage that is associated with an undeveloped drainage system. Late in the ablation season (period 3, DOY 201–220) shows the best agreement with observations which is probably due to a fully developed drainage system that does not introduce most of the above uncertainties. Water tends to stored subglacially early in the ablation season ({STRIKE}period periods 1 and 2), which is not captured in Model B and seen from the results in Figure 7, part A. Late in the ablation season (period 3) subglacial water storage will be less likely, which is also seen in Figure 8, part A, as the two curves converge toward the end of the measurement period. Comparing the correlation coefficients for period 1 with that of period 2 suggest that the undeveloped drainage system has a larger effect on the water discharge due to a smaller correlation value (Table 3). Furthermore, SnowModel is forced with a set of meteorological observations that may not be fully representative of the glacier conditions which also may result in errors and misfits against the observed water discharge.

The modeled suspended sediment concentration and transport agrees reasonably well with observations (Table 3). The amount of suspended sediment that leaves the glacier is linked to the water discharge through the simple representation described by Equation (1). The glaciofluvial erosion increases as a power function of the water discharge, which potentially yields too high erosion for a large water discharge because the amount of sediment available for suspension is geometrically restricted in the lumped element formulation of the sediment model. Assuming an unlimited amount of sediment available for suspension may not be valid when the water discharge is very large (Clarke, 2005), the amount of sediment available for glaciofluvial erosion at a given time depends on the balance between the amount of new sediment created by ongoing glacial erosion and the amount removed by glaciofluvial erosion. The assumption of inexhaustible supply is difficult to verify but it was tested indirectly by looking carefully at observations for two 4-day periods. The results indicate that the assumption of an infinite reservoir holds to a first approximation. However, the mean suspended sediment concentration for late period was slightly larger, which could be linked to an increased erosion rate through the melt period. The correlation between observation and Model A for period 3 compared with that of period 2 shows a small reduction, which could be linked to a change in the sediment supply limit; however, the assumption is used as a first approximation that can easily be adjusted in the model if field observations indicate limited sediment supply.

Changes in the subglacial conduit and storage system are likely to occur and it has been observed that they can be rapidly evolving features in Arctic glaciers and on the Greenland Ice Sheet (Bartholomaus et al., 2008; Sundal et al., 2011). Assuming a constant volume of the conduit system over the season will introduce an error in the modeled meltwater discharge from the glacier. This error will propagate to the modeled sediment transport as it is linked to the discharge through the modeled suspended concentration [Equation (6)]. Thus in Model A, it is anticipated that the modeled sediment transport should be too low early in the melt season when the conduit volume is overestimated and too high a value late in the melt season when the conduit volume is underestimated because the proglacial water discharge already has been influenced by the evolving drainage system through the ablation season. The modeled suspended sediment concentration and transport from Model A in Figures 7, part B, and 8, part B, illustrates well the influence of a constant volume of the drainage system. The cumulative daily values from period 1 are close to or underestimate observed values. For period 2 observation and Model A show similar values and for the last period Model A is clearly overestimating the suspended sediment transport. This could be linked with a calibration issue of the geometry of the drainage model which fits the middle period best. For example, the modeled suspended sediment concentration was shown to increase with a smaller cross-sectional area due to higher turbidity because the amount of water coming through the system is the same (Fig. 7, part B). In this case, the concentration of the suspended sediment would give unrealistically high values for too small cross-sectional areas and vice versa.

Model B behaves in a different way when compared to Model A, because the water available for the sediment model in the beginning of the runoff season is overestimated and slightly underestimated in the last part due to an insufficient representation of the drainage system and its development throughout the ablation season (Fig. 7). However, Model A and Model B are two different ways of forcing the sediment model. Model A is forced with the water flowing out of the glacier (proglacial observed, which has been under the influence of the englacial/subglacial drainage system), where Model B is forced with SMP from SnowModel that gives a water input into the glacier drainage system (which has not been under the influence of the englacial/subglacial drainage system). In this way, Model A takes into account the seasonal englacial/subglacial storage buildup and release of the water discharge within the drainage system, and Model B does not. Since the sediment model is based on critical shear stress at the bed in subglacial channels, the choice of water input through the ablation season will reflect the sediment output as the hydrological system evolves. The high correlation coefficients from Model A suggest that the simple shear stress connection at the bed between the subglacial water and the suspended sediment concentration is a good approximation for this glacier (Table 3). Moreover, the choice of the height and base area of the crevasse feeder (h_R, A_R) also controls how much water that flows into the conduit system. The maximum amount of water, controlled by the volume of the crevasse feeder in the conduit system, gives an upper limit to the amount of calculated suspended sediment that can leave the glacier system. Model A is not dependent on the evolution of the englacial/subglacial drainage system in the same way as Model B, since the actual water that leaves the glacier has already been through a seasonal developing drainage system. To get a good fit to the observed sediment transport for Model A is more a calibration issue when compared to Model B. Model B has no representation of seasonal subglacial storage and release processes (since SnowModel is a surface model, not a dynamic model), which is seen in Figure 8 as an overestimation of water discharge and suspended sediment transport for the first two periods. This omitted representation results in lower correlation coefficients when compared to Model A, and suggests that the omitted routines in SnowModel for evolution of the drainage system is the largest source for errors in Model B.

Furthermore, ice-dynamical processes were not taken into account in the establishment of the conduit system, which may introduce errors when the discharge calculations are made through the individual hydraulic elements. The area and volume of the conduit channels were kept constant in order to simplify the sediment transport calculations. In reality, the evolution of the original drainage system will be controlled by the balance between the water pressure in the conduit system and conduit closure due to ice flow (Röthlisberger, 1972; Schoof, 2010).

Conclusion

The sediment model formulated by Clarke (1996a, 1996b) was applied to the Mittivakkat Glacier system using a constant idealized drainage system. The sediment model performs reasonably well and captures most of the large sediment transports associated with high melting events. The calculated cumulative water discharge from SnowModel is $Q_{mod} = 3.93 \cdot 10^7$ m^3 and the observed water discharge is $Q_{obs} = 3.96 \cdot 10^7$ m^3, which gives a relative difference of 0.8%. The cumulative suspended sediment transport (SST) for Models A and B are $SST_{ModA} = 18{,}358$ ton and $SST_{ModB} = 17{,}745$ ton, which compare well with the observed SST of $SST_{obs} = 17{,}808$ ton. The relative differences with respect to the observed suspended sediment transport for the model runs are 3.0% looking at Model run A, and 0.4%, looking at Model run B, respectively.

The use of a constant idealized conduit system has introduced errors in the suspended sediment concentration and transport at the glacier terminus. These errors are to be expected due to the general simplicity of the whole glaciofluvial suspended sediment model. However, the results show that the modeled and observed values match reasonably well (Table 3), which gives us confidence that the lumped-element formulation can be used for calculating suspended sediment concentration and transport for glaciers in Greenland. The estimated SMP from SnowModel also adds to the limitations of the model results in the sediment model due to the direct link between the suspended sediment concentration and water discharge formulations. Whenever SnowModel fails to capture meltwater or rainfall events the output in suspended sediment concentration from the sediment model will begin to diverge from the observations.

The inclusion of a limited sediment reservoir and a temporally variable conduit system could potentially improve the sediment model presented here, especially if more observations of suspended sediment and discharge become available. Even with these limitations, the sediment model successfully captures the observed concentration and transport of suspended sediment, indicating that the assumption of an infinite sediment reservoir is valid.

The geometrical setup of the sediment model, including the choice of physical parameters, could thus be applied to geographically similar catchments, particularly if the SMP in SnowModel is constrained with a period of discharge measurements. Application to catchments including the Greenland Ice Sheet margin would require careful consideration of the geometrical input parameters and preferably validation from a period of observations of suspended sediment. However, the simple model approach shows that it is possible to produce reliable results on suspended sediment transport, which could be used to evaluate and quantify the effects of climate change on the glacier system. The system is suitable for modeling suspended sediments and can be used to evaluate and quantify the effects of climate change on a glacier system for period where no observations are available.

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