Suspended sediment transport in glacial meltwater during the initial quiescent phase after a major surge event at Kuannersuit Glacier, Greenland

Niels Tvis Knudsen, Jacob Clement Yde & Gry Gasser

Abstract

This paper describes a rough estimate of the suspended sediment transport in the bulk meltwater evacuated from Kuannersuit Glacier during the summers of 2000 and 2001. In 1995-98, an 11 km terrestrial surge of Kuannersuit Glacier, an outlet glacier of the largest ice cap on Disko Island, West Greenland, affected the catchment dramatically. The results show that in 2000, the daily sediment discharge was about 32,500 t day^{-1}, corresponding to a specific sediment load of 19,000 t km^{-2} year^{-1}. In 2001 the diurnal suspended sediment load was about 26,000 t day^{-1}, corresponding to a specific sediment load of 15,000 t km^{-2} year^{-1}. There was only a poor relation between meltwater discharge and suspended sediment transport, indicating that the drainage system was highly unstable. In 2001 the discharge and the sediment transport on several occasions was affected by collapse within the glacial drainage system and at the glacier margin. Assuming that suspended sediment transport and bedload is equal, the effective mechanical erosion is about 15 mm year^{-1}. Compared to the sediment transport from other parts of Greenland and High Arctic regions the transport during the surge event and in the early quiescent phase is significantly higher. This indicates the importance of glacier surge in initiating sediment transport pulses in cold regions.

Keywords

Suspended sediment transport, glacier surge, quiescent phase, Greenland

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In areas covered by temperate and polythermal glaciers and ice caps, glacial erosion and transport is responsible for large sediment yields (Hasholt, 1996). The sediment is normally transported in the basal zone towards the ice margin, where it can be deposited as various till types, or when meltwater is available, be evacuated with the bulk glacial meltwater mainly formed by ablation processes and ice movement. When the sediment leaves the glacier, it is usually either deposited in proglacial areas forming outwash deposits or in marine environments further away from the glaciers. It has been suggested that almost 25% of the global marine sedimentation has occurred in fiords over the last 10,000 years (Syvetski et al., 1986). Moreover, glacial and glaciofluvial sediments currently dominate sedimentation in high latitude environments (Hodson et al., 1998). The sediment yield from glaciers is highly dependent on the thermal regime and activity of the glacier. High rates are usually measured during glacier advance and at the beginning of the ablation period, whereas other researchers have reported both increased and decreased sediment availability during periods with increased discharge and/or reorganisation of the internal drainage system (Hodson and Ferguson, 1999). In contrast, catchments with little glacier ice cover deliver small quantities of sediment because the release of material is low within the basin (Bogen and Bønsnes, 2003).

In a review of field data on rates of erosion and sediment evacuation by glaciers Hallet et al. (1996) mention that glaciological variables such as sliding speed (temperate glaciers), glacier size, ice flux, meltwater production and meltwater routing to the glacier terminus, as well as the erosional susceptibility of the bedrock are significant. Whether any of the quoted glaciers belong to the surging type is not discussed. The sediment yield, calculated as the effective mechanical erosion rate (mm year^{-1}) from various temperate glacial environments in Norway, the Swiss Alps and Alaska, is highly variable, probably reflecting the above-mentioned variables. The results are either taken from specific investigations or calculated based on the assumptions that bedload equals suspended sediment load and bedrock density is 2.7 m^{-3}. In Norway, where most glaciers rest on Precambrian bedrock, the erosion rate is relatively low, varying between 0.06 and 0.96 mm year^{-1}, with a mean value of 0.33 mm year^{-1}. In the Swiss Alps, values range between 0.41 and 1.7 mm year^{-1}, with a mean value of 0.97 mm year^{-1}, reflecting both the difference in topography and the bedrock compared to Norway. In Alaska, much higher values are observed, varying between 5 and 60 mm year $^{-1}$, probably reflecting that the glaciers are generally much larger than in the two previous areas and have higher sliding velocities. On Svalbard, where glaciers are generally based on sedimentary rocks and the thermal regimes are cold or polythermal, the erosion rate varies between 0.08 and 1.0 mm year^{-1}. In another study on Svalbard, Bogen and Bønsnes (2003) found values of the specific sediment yield between 28 and 83 t km^{-2} year^{-1} at three small non-glacial catchments, corresponding to an effective erosion rate of only 0.01 - 0.03 mm year^{-1}. The information from Greenland on sediment yield is sparse and is mainly based on measurements and evaluations in specific areas in North and East Greenland (Andrews et al., 1994, Hasholt, 1996, Rasch et al. 2000, Stott and Grove, 2001, Hasholt et al., 2005). In these areas the specific sediment yield is variable ranging between 10 and 1000 t km^{-2} year^{-1}, corresponding to an effective erosion rate up to about 0.37 mm year^{-1}, reflecting both the glacier cover within the drainage basins and the activity of the glaciers. An effective erosion rate of about 0.01 mm year^{-1} was reported from three fiord districts in East Greenland (Andrews et al., 1994).

This paper presents a study of the suspended sediment transport in the main meltwater stream leaving the Kuannersuit Glacier based on measurements from a single day in July 2000 and from 10 days in July 2001, where the drainage system is probably still developing after a major surge event, which occurred in 1995-98 (Gilbert et al. 2002). Thus, the glacier is in the early part of the quiescent period. The focus will be upon relations between sediment transport and meltwater discharge and a comparison of the sediment evacuation from other glaciers.

Figure 1: *Location map of Kuannersuit Glacier, Disko Island, West Greenland.*

The study area

The Kuannersuit Glacier (69º 50' N, 53º 10' W; coded 1HB15017 in the regional glacier inventory by Weidick et al. (1992)), is the largest single glacier draining the northwestern part of the Sermersuaq ice cap (Storbræen) on Disko Island, West Greenland (Figure 1). Before the surge event, the glacier covered an area of about 91 km^{2}, determined from a topographic map measured in 1931-33 (Geodætisk Institut, 1941), with a drainage area of 109 km^{2} (Yde et al., 2005). On the map, the glacier drained through an outlet orientated northeast – southwest, below about 850 m a.s.l. On aerial photographs taken in 1964, the glacier terminus had retreated about 2 km; in 1985 the retreat had increased to about 2.5 km since 1931-33. On both photographs, the lower part of the glacier is sloping gently towards the terminus from the temporary snowline, the glacier surface is unbroken, and a loop-formed moraine ridge situated on the eastern side of the glacier tongue is visible. On the map, the main part of the accumulation area is situated between about 900 m and 1500 m.

The glacier belongs together with several others in the basin to the Disko-Nuussuaq surge cluster (Weidick, 1988). During 1995 – 1998, the glacier experienced a major surge event, where the glacier terminus advanced 10.5 km and approximately 2.5 km^{3} of ice were transported down-valley. The rapid change in glacier extent was followed by marked changes in the surface morphology of the glacier, from an almost even and gently sloping surface to heavily broken and crevassed (Yde and Knudsen, 2005). During the surge, as ice moved forward, several shear planes developed, integrating subglacially deformed material into the ice and probably eroding and transporting large amounts of material along the glacier bottom. Large amounts of meltwater were produced, which eroded and transported material below the glacier as well as along the margins. On the western side of a bend on the glacier about 7 km up-glacier from the terminus, an ice-dammed lake formed into which several glaciers in the northwestern part of the drainage system deliver their meltwater. They comprise glaciers coded 1HB15009-1HB15014 covering approx. 17.5 km^2 as reported by Weidick et al. (1992). In addition, 3-4 smaller streams on both the western and eastern sides of the glacier drain bulk water underneath the tongue below the bend.

After the surge event, the glacier terminated at about 50 m a.s.l., while the area covered by Kuannersuit Glacier increased from 91 km^2 to 103 km^2, and the catchment area of the glacier increased from 109 km^2 to 258 km^2. The lower part of the tongue is oriented north - south as it moved from one part of the valley system into another. The proglacial area overridden by the surge consisted of rigid basaltic Tertiary rocks and unconsolidated Quaternary deposits (Pedersen et al., 2001). The glacier is located within the continuous permafrost zone, indicating that it must have been cold-based at least in a marginal zone before the surge. The mean annual air temperature measured at Qeqertarsuaq on the south coast of Disko Island was -3.9º C (1960-1990), and measurements at Mellemfjord, northwest Disko Island, showed a mean annual air temperature of -7.8º C (1 September 1993 - 31 August 1994) as reported by Humlum et al. (1995), indicating that mean annual temperatures at Kuannersuit Glacier are probably as low as - 4 – -6 ºC at sea level. This is further emphasized by observations of pingos in the area.

Since the surge ended, more than 90% of the meltwater discharge has left through an outlet on the western side of the glacier. On the eastern side a small stream also drains water from the glacier, and up-welling water is observed in several places on the outwash plain in front of the glacier.

Field and analytical methods

The main study period was 14-25 July 2001, during which 67 water samples were manually collected at the river bank in pre-rinsed 250 ml polypropylene bottles about 200 metres down-stream the meltwater portal with an interval of 3-6 hours. On 26-27 July 2000, sampling resolution was higher, with a 1-2 hour interval resulting in the collection of 20 samples. At the site, samples for determination of solute transport (Yde et al., 2005) and $\delta^{18}O$ variations (Yde et al., 2003) were collected simultaneously with the samples for suspended sediment transport.

Upon arrival in Denmark the suspended sediment content was determined by filtering the water and sediment samples through 0.45 μm cellulose nitrate membranes, which were dried at 110º C and weighed. Then the water volume of the sample was determined. The filter with sediment was then dried and weighed, and after subtraction of the filter the sediment weight was calculated. Finally, the sediment concentration in the sample was calculated. The content of organic material was determined by a LECO furnace to constitute about 0.25 % of the suspended sediment (Yde et al., 2005). The precision of suspended sediment concentration determination is within ± 4 %.

The discharge from the basin during 2000 and 2001 was determined at a hydrometric station about 4 km down-valley, where all water leaving the basin runs in a single stream before entering the braided delta at the head of the fiord, Kuannersuit Sulluat. The discharge comprises water from glaciers, snowfields, lakes and small water streams in the drainage basin, which covers a total area of 533 km^2. In both years about 85 % of the water was discharged from Kuannersuit Glacier before joining with bulk waters from adjacent glaciers and smaller streams further down-valley (Thorsøe, 2002).

Results

Figure 2 presents the suspended sediment concentration (SSC) record of 20 samples collected in the meltwater stream from 26 July 0900 hours to 27 July 0900 hours in 2000. The SSC varies between 13.1 g l^{-1} at 2330 hours and 7.7 g l^{-1} at 0900 hours, with a time-integrated mean value of 10.9 g l^{-1}. The average discharge is inferred from measurements on 24 July and 1 August further down-valley, giving values of 38.8 and 41.5 m^3 sec^{-1}, of which about 85 % comes from Kuannersuit Glacier. The period was dominated by cool and cloudy conditions and several precipi-

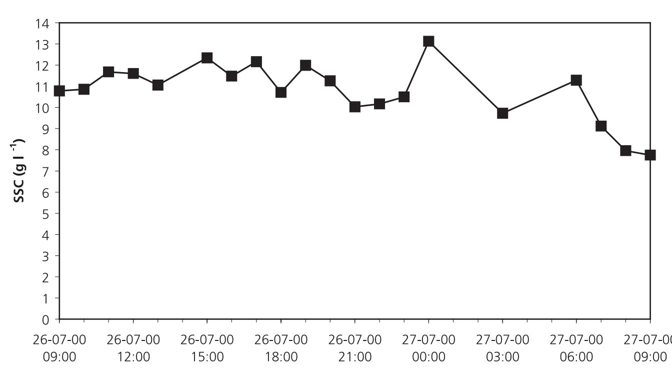

Figure 2: *Diurnal time series of suspended sediment concentrations (SSC) in bulk meltwater emanating from Kuannersuit Glacier during the period 26 – 27 July 2000.*

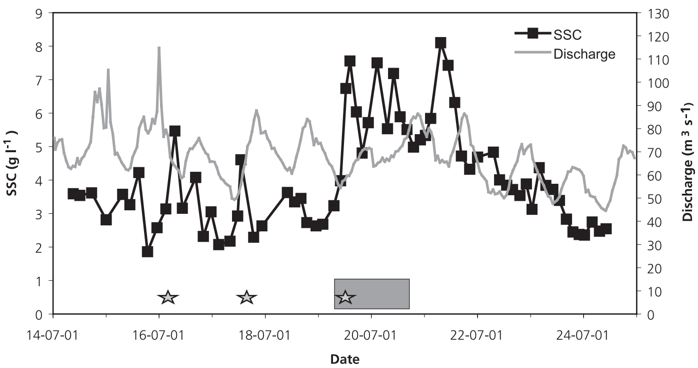

Figure 3: *Time series of suspended sediment concentrations (SSC) and discharge at the main meltwater outlet of Kuannersuit Glacier during the period 14 – 25 July 2001. The stars denote observation times of major ice-marginal collapses, and the grey rectangle indicates a period of precipitation.*

tation events. This indicates a mean discharge of about 35 m^3 sec^{-1} at the glacier terminus. The sediment flux is about 382 kg s^{-1}, which is equivalent to 33,000 t day^{-1}. A first order approximation of the specific sediment yield using a runoff period of 150 days and a catchment area of 258 km^2 gives a value of 19,200 t km^{-2} $year^{-1}$.

Figure 3 shows a time series of SSC measurements and discharge variations through the 2001 sampling period. The SSC varied between 1.9 and 8.1 g l^{-1}, with a time-integrated mean value of 4.0 g l^{-1}. The calculated suspended sediment transport (SST) varies between 114 and 532 kg s^{-1}, with a time-integrated mean sediment discharge of 267 kg s^{-1}, equal to 23,100 t day^{-1}. A first order approximation of the specific sediment yield using a runoff period of 150 days (1 May to 30 September), where the air temperature in the area mainly is above 0 ºC, gives a value of 13,400 t km^{-2} $year^{-1}$.

The discharge during the observation period in 2001 was markedly higher than in 2000, with a mean discharge during the observation period of 68 m^3 s^{-1}. It showed diurnal fluctuations of 20 m^3 s^{-1} during a period dominated by clear sky and low wind speed, and only a short period of overcast weather with precipitation. On the nights between 14/15 July and 15/16 July two distinct increases in discharge took place. The second increase coincided with the observation of a major ice-marginal collapse causing temporary blockage of the main outlet. On the hydrograph (Figure 3), short-term variations in discharge are seen before the increase, indicating disturbance of water runoff not associated with the normal diurnal variation caused by ablation. Observations from other glaciers indicate that such short-lived events are caused by rainfall or collapses within the subglacial drainage system temporarily impeding the discharge (Ballantyne and McCann, 1980; Russell et al., 1995; Stott and Grove, 2001). The water was delayed and later released in a major burst, which caused undermining of the ice-margin and subsequent collapse. The first increase on 15 July was not followed by frontal collapse, but a decrease in discharge was observed before the burst. The collapse seen on 16 July was followed by a burst and an increase in SSC. Later, two collapses were observed, the last one coinciding with a period of rainfall. Both of these events resulted in increased SSC, but no flood peaks were recognised. This could suggest gradual release of dammed water. The sudden increase in SSC on 19 July resulted in a three-day period of high sediment flux. Throughout the sampling period many more collapses could have happened within the subglacial drainage system as on several occasions large amounts of ice were released from the glacier, mainly during high discharge, and eventually deposited on the outwash plain in front of the glacier.

Figure 4 shows a comparison between log-log associated regression estimates and SSC measurements. If all measurements are used, the rating curve ($SSC = 1.47Q^{0.23}$; $p = 0.406$) is significantly influenced by the anomalously high concentrations during the 19 – 21 July event. However, the sediment yield is 9,800 t km^{-2} $year^{-1}$, suggesting that the discharge used by simple extrapolation is over-estimated. If only measurements from the period 15 – 18 July are applied, the rating curve ($SSC = 15.6Q^{-0.39}$; $p = 0.299$)

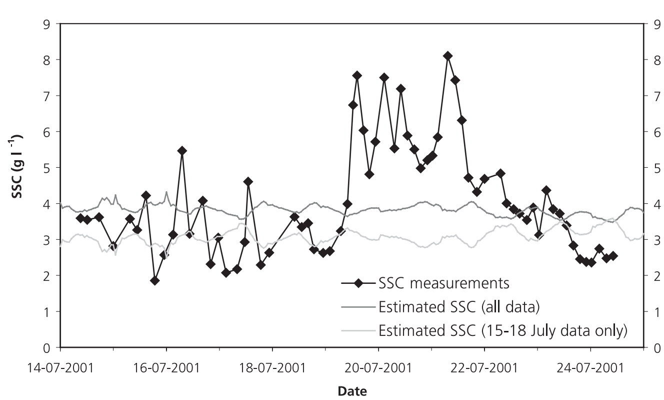

Figure 4: *Time series of log-log associated regression estimates compared to measured suspended sediment concentrations (SSC) at Kuannersuit Glacier during the sampling period 14 – 25 July 2001. A dark grey line denotes the regression estimate using all measurements, whereas a light grey line denotes the regression estimate using 15 – 18 July measurements. The drastic change in SSC, 19 – 21 July, is not reflected in the estimates.*

Year	Estimation method	Mean SSC (g l^{-1})	Mean SST (kg s^{-1})	Sediment yield (t km^{-2} year^{-1})	Effective erosion (mm year^{-1})
1997	Simple extrapolation	11.9	363	18,200	13.5
1999	Simple extrapolation	11.5	978	49,100	36.4
2000	Simple extrapolation	10.9	382	19,200	14.2
2001	Simple extrapolation	4.0	267	13,400	9.9
	Regression (all data)		261	9,800	7.2
	Regression (15–18 July data only)		206	7,700	5.7

Table 1: *Sediment flux estimates for the Kuannersuit Glacier catchment. Mean SSC and mean SST are derived from spot measurements (1997; 1999) or time-integrated mean values during sampling periods (2000; 2001). The mean SSC in 1997 is calculated from a spot sample of 4.1 g l^{-1} collected at a location 12 km downstream (Møller et al., 2001; Rasch et al., 2003) and assuming that a ratio of 2.8 between the locations is valid (Gilbert et al., 2002). The mean SST in 1997 and 1999 is calculated from single measurements of discharge (Møller et al., 2001), and assuming that 85 % of the total discharge is derived from the Kuannersuit Glacier catchment. Sediment yield is computed by assuming a constant catchment area of 258 km^2, and the duration of runoff is 150 days for all years. Regression estimates of sediment yield are derived from the method applied by Yde et al. (2005). Effective erosion is calculated assuming a representative rock density of 2.7 t m^{-3} and that the bedload is equal to the suspended load.*

provides an estimate relatively unaffected by transient flush events. The latter regression estimate indicates a conservative sediment yield of 7,700 t km^{-2} year^{-1}.

Discussion and conclusions

A summary of sediment flux estimates associated with the 1995-98 surge event of Kuannersuit Glacier is presented in Table 1. Rasch et al. (2003) compared suspended sediment samples from nine catchments on Disko Island collected in July 1997. Their measurements indicate relatively high SSC from the river draining the Kuannersuit Glacier catchment. During the surge, about 13,000 t day^{-1} of suspended sediment was delivered in 1997 to the fiord from the entire basin (Gilbert et al. 2002). The observations in 2000 indicate that the delivery of suspended sediment from the surging glacier alone was about 33,000 t day^{-1}, corresponding to a specific suspended sediment load of 19,200 t km^{-2} year^{-1}, of which large amounts are probably derived from the area directly influenced by the glacier surge. In 2001 the sediment discharge had decreased by about 30% to 23,100 t day^{-1}, corresponding to a specific suspended sediment load of 13,400 t km^2 day^{-1}.

Besides the suspended sediment load there is a marked bedload, which is probably as large as the suspended load. This is supported by the successive formation of a large outwash plain in front of the glacier. It indicates that during large parts of the surge period and in the early quiescent phase, the effective mechanical erosion rate varied between 10 and 36 mm year^{-1} (Table 1). The figures indicate that sediment transport increased during the surge and was at its highest when an effective erosion rate of about 36 mm year^{-1} was determined towards the termination of the surge and then declined in the early part of the quiescent period. The effective mechanical erosion rate estimated during the active surge and the early part of the quiescent phase indicates that glacier surges are very effective in providing sediments to the proglacial environment compared to the quiescent period. Furthermore, the sediment yield is higher than previously reported sediment yields from Greenland and other High Arctic environments, which are within the range 0.05 – 1.0 mm year^{-1}. A comparison with temperate environments indicates that only Alaskan glaciers reach comparable erosion rates. It is therefore to be expected that the amount of evacuated sediment from Kuannersuit Glacier during the surge and the early quiescent phase could be as high as the amount evacuated during the remaining quiescent period, which probably lasts at least 100 years (Yde and Knudsen, 2005).

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