Surge of a small East Greenland glacier, 2001–2007, suggests Svalbard-type surge mechanism

INTRODUCTION

Clusters of surge-type glaciers occur in many areas peripheral to the Greenland ice sheet (Weidick, 1988). In East Greenland (68–72° N), 30–70% of glaciers are of surge type, but only five of these have been described (Jiskoot and others, 2003, and references therein). Regional surge characteristics and dynamics have been used to suggest a hydrologically controlled surge mechanism, with surge behaviour that is more Alaskan-type than Svalbard-type in this region (Jiskoot and others, 2001, 2003; Murray and others, 2002, 2003; Pritchard and others, 2005).

A small unnamed valley glacier (70°7′39″N, 26°56′42″W) draining into Gåsefjord, Scoresby Sund, advanced 2.8 km during a recent surge (Fig. 1a). We unofficially name this glacier Sermeq Peqippoq, Greenlandic for 'glacier that bends'. The glacier is partly fed from the Geikie Plateau ice cap, and winds its way through a valley where four tributaries converge with the main flow unit (some class III, $R_a > 1$; Kargel and others, 2005). In 2000, the glacier was 10 km long, had an area of 21 km^2, an elevation range of 2100–800 m a.s.l. and an average slope of 7.4°. On the basis of 1987 aerial photographs, it was classified as possibly of surge type with one surge feature (looped moraines; Jiskoot and others, 2003) and described as a 'landbased, depleted and retreated valley glacier with a compound cirque basin, clear elongated moraine loops and a possible Little Ice Age terminal moraine complex in the sea, about 6 km in front of the 1987 margin (Jiskoot, unpublished database). The glacier overlies Tertiary age hyaloclastite basalts, while at maximum surge extent it reaches Middle Proterozoic migmatic gneiss (Bengaard and Hendriksen, 1984). Sermeq Peqippoq is one of the smaller East Greenland glaciers with an observed surge. Other surging glaciers in the region range in length from 6 to 82 km (Jiskoot and others, 2003). Here we describe the results of a remote-sensing study aimed at a detailed examination of the surge behaviour and dynamics of Sermeq Peqippoq during the period 2000–08, and comparison of these with known types of surge behaviour.

METHODOLOGY AND RESULTS

Eleven Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) level 1B images were obtained from the NASA Earth Observing System Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/) and georeferenced to two orthorectified Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images from the US Geological Survey (USGS) Earth Explorer (http://edcsns17.cr.usgs.gov/EarthExplorer/), covering the period June 2000–July 2008. Danish Cadastral Survey (KMS) digital aerial photographs from 1981 (878G1154) and 1987 (888H1481) were consulted for quiescent-phase terminus positions and morphology. Frontal advance, feature tracking of elongated moraine loops and a surge bulge were measured in ENVI 4.5 from summer images at ~1 year intervals (Fig. 1). Quiescent-phase velocity is assumed to be equal to creep velocity (Murray and others, 2003) and is 0.01 m d^{-1} (baseline displacement rate in Fig. 2) for an average ice thickness of 100–125 m.

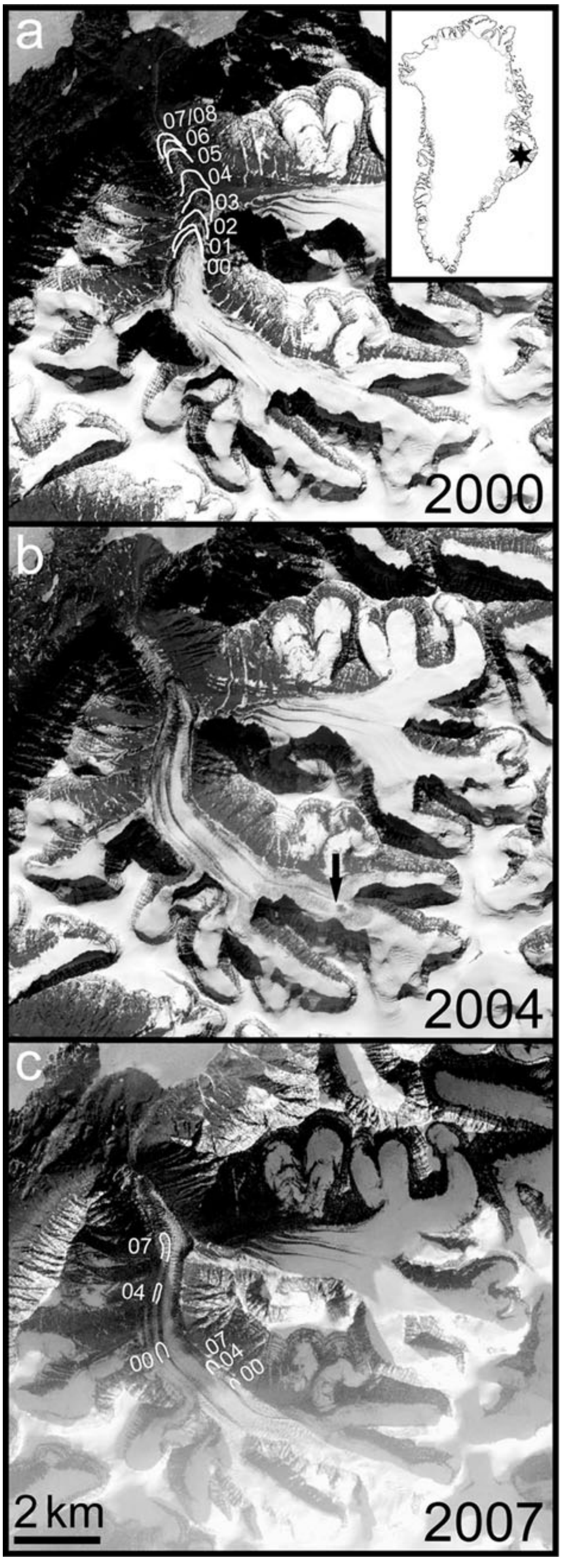

Fig. 1. Glacier location map, and surge progression shown on ASTER satellite imagery. (a) Pre-surge image of 25 June 2000 with terminus positions between 2000 and 2008. (b) Full-surge image of 18 June 2004 showing a crevassed surface and 1.6 km advance. Arrow indicates probable zone of surge initiation. (c) Late-surge image of 19 June 2007, where the glacier negotiated a left bend in the valley and extended to its full advance of 2.8 km. The positions of the 2000, 2004 and 2007 moraine loops are superimposed. The eastern moraine loop is virtually stagnant after 2004.

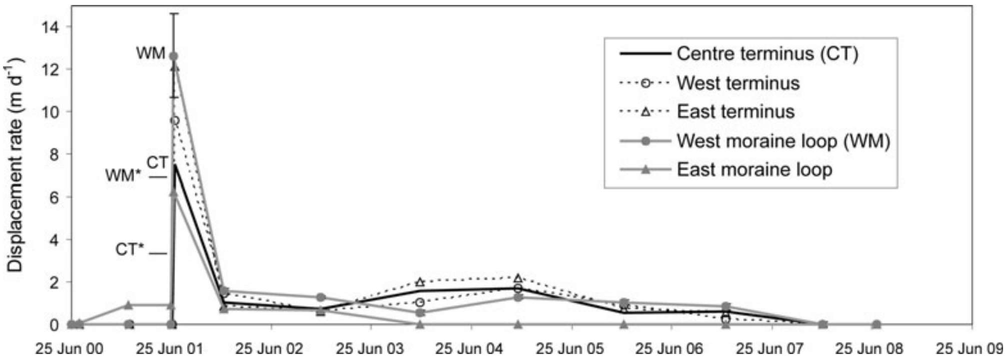

Fig. 2. Ice displacement rates constructed from frontal advance of the centre, east and west sides of the glacier terminus and by feature tracking of the two elongated moraine loops in Figure 1c. The east moraine loop speed of 0.9 m d^{-1} between 2000 and 2001 is based on the surge-bulge propagation rate. Displacement rates for the centre terminus and west moraine loop are indicated for a 20 June 2001 (WM and WT) surge initiation in the line graph and for a possible 2 June 2001 surge initiation (CT* and WM*) with horizontal markers. Error bars on the west moraine loop curve are maximum errors for the displacement rates.

Morphological changes during the surge include a 2.8 km advance, extensive crevassing, a drawdown of the upper glacier evidenced by trimlines, displacement of medial moraines and elongation of moraine loops, frontal steepening, the formation of a large ($\sim$280 m $\times$ 160 m) supraglacial lake and the pre-surge development of a surge bulge (Figs 1 and 3). The propagation of crevasses, distribution of drawdown and the lake location suggest the surge started in the upper part of the main flow unit (Fig. 1b), propagating mainly down-glacier and only $\sim$500 m up-glacier. The whole of the eastern tributary was affected, but the three western tributaries only in their lower reaches. The eastern tributary loop was pinched off by the main flow in 2004 and remained virtually stagnant thereafter. Because the supraglacial lake is only fully developed in the 12 July 2001 and 24 June 2002 images, we infer that in the initial year of the surge high water pressures may have occurred. Yet, proglacial streams and lakes did not change in morphology or location over the period 2000–08, suggesting that no catastrophic discharge event occurred. During the advance (mainly between 2002 and 2004), the glacier 'spilled' into the valley to the east, causing an apparent temporary slowdown, mostly of the eastern part of the terminus.

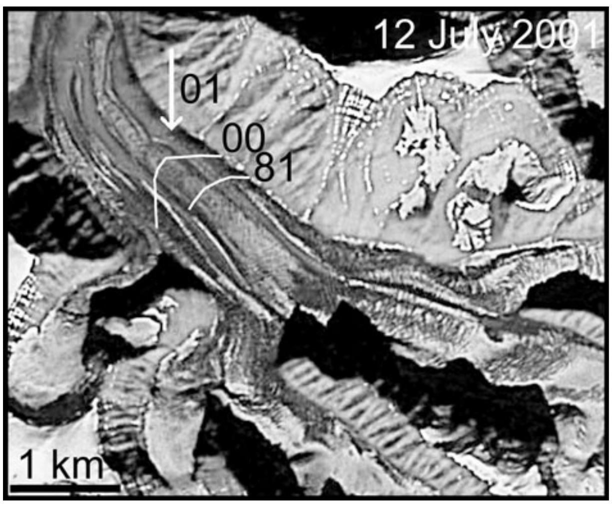

Fig. 3. Landsat 7 image of 12 July 2001 showing positions of the surge bulge in 1981, 2000 and 2001 (arrow). Heavy crevassing and evidence of pre-surge glacier surface trimline and drawdown on the north valley wall occur only upstream of the 2001 bulge, while later in the surge the downstream region is also extensively crevassed.

Sermeq Peqippoq's last pre-surge image is from 1 June 2001, and the first surge image from 12 July 2001. During this period the glacier advanced 144 m. A surge front/bulge (Fig. 3) in the July 2001 image suggests that the surge started not long before 12 July 2001. This bulge occurs in other pre-surge images and had travelled $\sim$760 m downstream since 1981, with average propagation speeds of 0.07 m d^{-1} (August 1981–August 2000) and 0.9 m d^{-1} (August 2000–July 2001). This bulge also implies that the surge initiated up-glacier, in the main flow unit, and that frontal advance occurred sometime after surge initiation. The approximate time difference between surge initiation and surge advance mainly depends on the surge front propagation, which ranges from 2.7–4.9 m d^{-1} for Bakaninbreen, Svalbard, (Murray and others, 1998) to 90 m d^{-1} for Bering Glacier, Alaska, USA, (Roush and others, 2003) and 250 m d^{-1} for up-glacier Sortebræ, East Greenland (Pritchard and others, 2005). Raymond and others (1987) separated Variegated Glacier, Alaska, into a surge zone (>20 m d^{-1}), front zone (>40 m d^{-1}) and stagnant zone ($\sim$0 m d^{-1}), where the bulge separated the surge and front zones. Since Sermeq Peqippoq's terminus advanced while the bulge was still 1200 m upstream of the margin, we also suggest that its surge bulge separates the up-glacier surge zone from the down-glacier front zone. We calculated the time difference between the surge reaching the moraine loops and the terminus based on a measured ratio of $\sim$3 : 2 for the displacement rate of the west moraine loop and the advance rate of the centre terminus in straight valley stretches later in the surge. In order to achieve a ratio of 3 : 2 for these two flow rates, the surge-initiation time lag between the moraine loops and the glacier terminus is $\sim$7 days. This results in a surge-bulge propagation rate during full surge of $\sim$170 m d^{-1}. This 7 day time lag is used in the calculations of surge initiation and initial surge displacement rate between 1 June and 12 July 2001 (Fig. 2).

Lingle and Fatland (2003) state that a (temperate) glacier will not surge until meteorological conditions occur that store large amounts of englacial water, resulting in a common late-winter to spring surge onset. For Svalbard, Hodgkins (1997) shows a build-up of englacial water towards the end of summer, followed by winter storage and release in the following summer, implying that enhanced precipitation in late summer of the previous year might help trigger a surge the following spring. In order to determine weather conditions that could be conducive to the surge initiation, Danish Meteorological Institute weather data (http://www.dmi.dk/dmi/index/gronland/vejrarkiv-gl.htm) for 2000 and 2001 were obtained for the nearest weather station, Ittoqqortoormiit (formerly Scoresbysund). Unfortunately, this station is 190 km east of Sermeq Peqqipoq and has a more maritime (polar) climate, with higher precipitation and more moderate temperatures. We therefore only use the general weather patterns. In 2001, regular positive maximum temperatures at Ittoqqortoormiit occurred from 5 May onwards, and regular positive minimum temperatures from 23 June onwards. In January and February 2001, snowfall amounts were well above average (200%), and for the 2000/01 winter season (October–April) snowfall was 115% of normal, while rainfall was 133% of normal in October. The first rain in 2001 was a multi-day event between 14 and 19 June.

We postulate three possible scenarios for the start date of the surge: (1) the first day after the last pre-surge image, 2 June; (2) immediately after the first period of rain and/or after a prolonged period of >0°C temperatures, 20 June; and (3) 1–2 days before the first surge image, 10 July. Scenario 3 is unlikely given the large displacement rate required (>100 m d^{-1}), which would have resulted in more extensive crevassing than observed on 12 July 2001. Figure 2 shows the data coincident with a 20 June start (considered close to the most likely surge initiation date), but we also indicate the displacement rates for the west moraine loop (WM*) and the centre terminus (CT*) for a 2 June start. Sermeq Peqippoq's maximum flow rates are 5–15 m d^{-1}, decreasing rapidly to <2 m d^{-1} after 1 year, then gradually to <1 m d^{-1} in 2007 and quiescence velocities in 2008. The surge terminated around or just before June 2007, as no measurable displacement occurred in the glacier between June 2007 and July 2008.

Although the surge proper started between 2 June and 12 July 2001, the surge initiation probably occurred over months to a year as the surge-bulge displacement rate increased from 0.07 to 0.90 m d^{-1} between August 2000 and July 2001. This is comparable to the slow increase in velocity in the first 2 years of Svalbard surges (Murray and others, 2002). Assuming that the previous surge extended to the same position as the current surge, and that the pre-1981 retreat rate was comparable to that between 1987 and 2000 (38 m a^{-1}), the previous surge might have occurred around 1941. Sermeq Peqippoq therefore has a quiescent phase of at least 60 years and an active phase of 6–7 years.

DISCUSSION AND CONCLUSIONS

Sortebræ, 125 km south of Sermeq Peqippoq, surged in the 1950s and between 1992 and 1995, and has surge behaviour suggesting that it has Alaskan-type surge dynamics with a rapid mid-winter initiation, a sudden termination coincident with rapid release of stored water, sustained surge flow rates of up to 24 m d^{-1}, a surge phase of 28–32 months and a quiescent phase of 39–49 years (Jiskoot and others, 2001; Murrray and others, 2002; Pritchard and others, 2005). In contrast, Sermeq Peqippoq's surge behaviour indicates a multi-phase surge, with an acceleration phase over several months and a surge phase with gradual deceleration over 6–7 years to quiescence. Maximum surge velocities and advance rates are <13 ± 2 m d^{-1}, and prolonged surge velocities only 1–2 ± 0.1 m d^{-1}, and there is no evidence for rapid discharge events. Quiescence is at least 60 years. These are all surge characteristics typical of Svalbard surges (Murray and others, 2003). Surge phases for other East Greenland glaciers are 5–15 years, and quiescent phases 70–200 years (Jiskoot and others, 2001), indicating that Sortebræ may be an exception for this region. This suggests that Sermeq Peqippoq and most other surge-type glaciers in this region could have a surge mechanism similar to that in Svalbard, which is probably thermally controlled, rather than to that in Alaska and other temperate regions, which is probably hydrologically controlled (Murray and others, 2003). Furthermore, if more surges were of Alaskan type, with shorter quiescent phases, more active surges would be detected on available imagery.

The inferred thermal regime is corroborated by icing in front of many land-based glaciers in the Scoresby Sund region. Furthermore, the region is a transition zone from continuous to discontinuous permafrost (Stablein, 1984; Lie and Paasche, 2006), and some glaciers in the Stauninger Alps have measured polythermal regimes (Kirchner, 1963; personal communication from R. Mottram, 2009). Therefore, smaller surge-type glaciers might exhibit Svalbard-type surges, while the larger (mostly tidewater) glaciers along the Blosseville Kyst (e.g. Sortebræ) are likely more temperate and exhibit Alaskan-type surges. The combination of both types of surge behaviour in this region, coinciding with a transition in thermal regime, the slow development of a surge bulge on Sermeq Peqippoq and the absence of a discharge event, suggests that the two surge mechanisms postulated by Murray and others (2003) are indeed thermally differentiated, rather than substrate, climate or glacier morphology differentiated.

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REFERENCES

Bengaard, H.-J. and N. Henriksen. 1984. *Geological map of Greenland, 1:500000, Sheet 12, Scoresby Sund*. Copenhagen, Geological Survey of Greenland.

Hodgkins, R. 1997. Glacier hydrology in Svalbard, Norwegian High Arctic. *Quat. Sci. Rev.*, **16**(9), 957–973.

Jiskoot, H., A.K. Pedersen and T. Murray. 2001. Multi-model photogrammetric analysis of the 1990s surge of Sortebræ, East Greenland. *J. Glaciol.*, **47**(159), 677–687.

Jiskoot, H., T. Murray and A. Luckman. 2003. Surge potential and drainage-basin characteristics in East Greenland. *Ann. Glaciol.*, **36**, 142–148.

Kargel, J.S. *and 16 others*. 2005. Multispectral imaging contributions to Global Land Ice Measurements from Space. *Remote Sens. Environ.,* **99**(1–2), 187–219.

Kirchner, G. 1963. Observations at bore holes sunk through the Schuchert Gletscher in north-east Greenland. *J. Glaciol.,* **4**(36), 817–818.

Lie, Ø. and Ø. Paasche. 2006. How extreme was northern hemisphere seasonality during the Younger Dryas? *Quat. Sci. Rev.,* **25**(5–6), 404–407.

Lingle, C.S. and D.R. Fatland. 2003. Does englacial water storage drive temperate glacier surges? *Ann. Glaciol.,* **36**, 14–20.

Murray, T., J.A. Dowdeswell, D.J. Drewry and I. Frearson. 1998. Geometric evolution and ice dynamics during a surge of Bakaninbreen, Svalbard. *J. Glaciol.,* **44**(147), 263–272.

Murray, T., T. Strozzi, A. Luckman, H. Pritchard and H. Jiskoot. 2002. Ice dynamics during a surge of Sortebræ, East Greenland. *Ann. Glaciol.,* **34**, 323–329.

Murray, T., T. Strozzi, A. Luckman, H. Jiskoot and P. Christakos. 2003. Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions. *J. Geophys. Res.,* **108**(B5), 2237. (10.1029/2002JB001906.)

Pritchard, H., T. Murray, A. Luckman, T. Strozzi and S. Barr. 2005. Glacier surge dynamics of Sortebræ, east Greenland, from synthetic aperture radar feature tracking. *J. Geophys. Res.,* **110**(F3), F03005 (10.1029/2004JF000233.)

Raymond, C., T. Jóhannesson, T. Pfeffer and M. Sharp. 1987. Propagation of a glacier surge into stagnant ice. *J. Geophys. Res.,* **92**(B9), 9037–9049.

Roush, J.J., C.S. Lingle, R.M. Guritz, D.R. Fatland and V.A. Voronina. 2003. Surge-front propagation and velocities during the early-1993–95 surge of Bering Glacier, Alaska, U.S.A., from sequential SAR imagery. *Ann. Glaciol.,* **36**, 37–44.

Stablein, G. 1984. Geomorphic altitudinal zonation in the arctic–alpine mountains of Greenland. *Mt. Res. Dev.,* **4**(4), 319–330.

Weidick, A. 1988. Surging glaciers in Greenland: a status. *Grønl. Geol. Unders. Rapp.* 140, 106–110.