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Spatial and temporal variations in lakes on the Greenland Ice Sheet

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ABSTRACT

Surface lakes on the Greenland Ice Sheet provide temporary storage for meltwater that influences both the surface and basal water fluxes. Thus, to understand the effects of variations in surface melt on ice sheet dynamics it is necessary to understand the surface hydrology. We have used satellite imagery, acquired at 5-day intervals, to map lake initiation and cessation on two sub-sections on the south west Greenland Ice Sheet over three melt seasons (2007–2009). We observe that lake initiation is closely tied to a threshold energy input of approximately 40 ± 18.5 positive-degree-days. This applies to all studied melt seasons, regardless of evolution and melting index anomalies. Lake longevity averages 24 days with little variation between different melt seasons. Our observed median lake area is larger than previously reported. Approximately 50% of all lakes have a life span of <10 d. Cessation of identified lakes is caused by two processes: drainage during the melt season (88% – 2007, 78% – 2008 and 88% – 2009) and freeze-up at the end of the season (12% – 2007, 22% – 2008 and 12% – 2009). Inclusion of the energy needed for lake initiation and number of lakes that freeze up at the end of the season into supra-glacial lake models will add further insight into the hydrological system dynamics.

1. Introduction

Supra-glacial lakes form every melt season along most of the ablation zone on the Greenland Ice Sheet (GrIS), the exception being along the southern east-coast. These lakes were first noted by Echelmeyer et al. (1991) and have recently been more widely studied (e.g. Lüthje et al., 2006; McMillan et al., 2007; Das et al., 2008; Georgiou et al., 2009; Sundal et al., 2009; Palmer et al., 2011; Selmes et al., 2011). Melt water accumulates in depressions on the ice in the form of lakes and together with supra-glacial rivers provide temporal storage of melt water on the GrIS. In the beginning of the melt season the lakes are confined to areas near the ice sheet margin but once the melt season progresses they develop at higher elevations inland and form a supra-glacial hydrological system. The lakes can terminate in two ways: drainage (Das et al., 2008; Selmes et al., 2011) and freezing (Selmes et al., 2011). Das et al. (2008) showed that lake drainage can be fast (<2 h) and that water can reach the ice sheet bed. Out of all lakes on GrIS 13% drain over a time period of maximum 2 d (Selmes et al., 2011).

The existence of water at an ice sheet base enhances basal sliding and increases mass fluxes to the ice sheet marginal zone. Increased surface velocities have been shown to coincide with increased surface melting (e.g. Zwally et al., 2002; Joughin et al., 2008; Bartholomew et al., 2010; Hoffman et al., 2011) due to enhanced basal sliding (e.g. Rignot and Kanagaratnam, 2006; Shepherd et al., 2009; Lampkin and VanderBerg, 2011). Alley et al. (2005) and van der Veen (2007) demonstrated that surface crevasses can propagate to the bed even under cold conditions, provided that crevasses are over-pressurized by an ample supply of meltwater during formation. Surface lakes facilitate such over-pressurization through their large storage volumes (Das et al., 2008).

The lakes have mainly been studied using satellite images from Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) (e.g. Lüthje et al., 2006; McMillan et al., 2007; Georgiou et al., 2009; Sundal et al., 2009), Landsat-7 Enhanced Thematic Mapper Plus (ETM+) (e.g. McMillan et al., 2007; Lampkin and VanderBerg, 2011) and Moderate resolution Imaging Spectroradiometer (MODIS) imagery on the Aqua and Terra satellites (e.g. Sundal et al., 2009; Selmes et al., 2011). In this paper, we exploit MODIS images from 2007, 2008 and 2009 and analyze lakes on a sub-section of the south-west coast of GrIS. The use of melt seasons with different temperature evolution, both regarding length of the melt season and strength of the melt season, enables estimates of energy needed for lake initiation. The lake initiation was found to be constrained to a predictable energy contribution. Lakes with floating ice have been incorporated into the study and due to their above average size this might affect the lake area estimates. As stated by Liang et al. (2012) this has not previously been done using MODIS images. Their large size may imply a large lake volume,

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hence indicating an increased available melt water volume. Lake longevity was investigated and connected to elevation and spatial distribution. Mechanisms responsible for lake cessation was further examined where the relative importance of the different mechanisms, drainage and freeze-up was investigated.

2. Study areas, satellite images and method

We acquired MODIS images over two study areas, A1 and A2, of West Greenland, covering 147,000 km^2 (A1) and 78,500 km^2 (A2) (Fig. 1). A1 was used for our primary study and A2 was used for verification of our results. Information given below on number of images used for 2008 is valid for both the study areas. A total of 19 MODIS images from 2007, 21 from 2008 and 18 from 2009 were used and a period of May to October was investigated. The melt season of 2007 was chosen based on the extreme annual melt volume in that year (Tedesco et al., 2008) and the years 2008 and 2009 were chosen since the standardized melting index anomaly for the years 1979–2009 showed that they have a value close to zero (Tedesco et al., 2011). A1 was located just north of the study area used by Sundal et al. (2009) and A2 was located within the study area used by Sundal et al. (2009) and overlapping the northern part of the study area used by Lüthje et al. (2006). A2 was selected to provide as many cloud free images as possible for the melt season of 2007.

We have also used mean daily air temperature data collected by the Danish Meteorological Institute (DMI) at Kangerlussuaq (Fig. 2b, d and f) and applied monthly lapse rates established by Fausto et al. (2009). We compared the lapse rate adjusted temperature record from 2007, 2008 and 2009 with measured temperatures from the ice sheet along the K-transect (van den Broeke et al., 2009) and with measured data from 2009 (van As et al., 2012); (starting fall 2008 and ongoing) (Fig. 1). We found a difference between calculated and measured temperatures at the measurement sites of approximately −3 °C, likely caused by the colder boundary layer over the ice sheet surface (e.g. van den Broeke et al., 2009). Consequently we have applied a −3 °C offset to the Kangerlussuaq data before calculating the lapse rate adjusted temperatures.

In order to investigate the timing of lake initiation we considered cumulative positive degree days (PDDs) as a proxy for the incident energy available for melting. The use of PDD enables com-

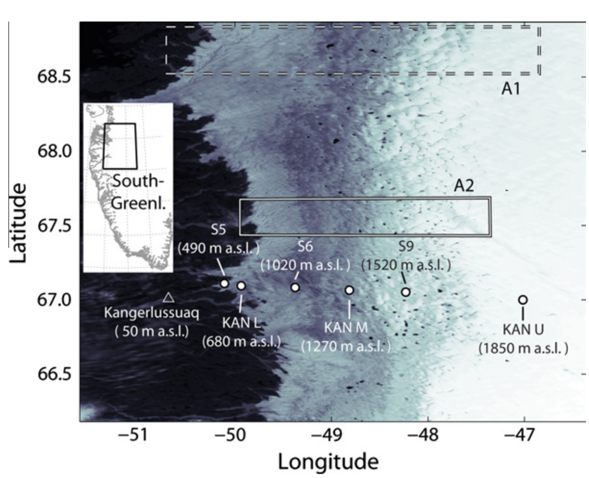

Fig. 1. MODIS image from 16 July (Julian Day 198) 2008. The study areas considered A1 (dashed line rectangle) and A2 (solid line rectangle). Filled circles indicate the locations of the ice sheet weather stations used in the study and the triangle indicate the Kangerlussuaq weather station. The inset map of southwest Greenland shows the area covered by this image.

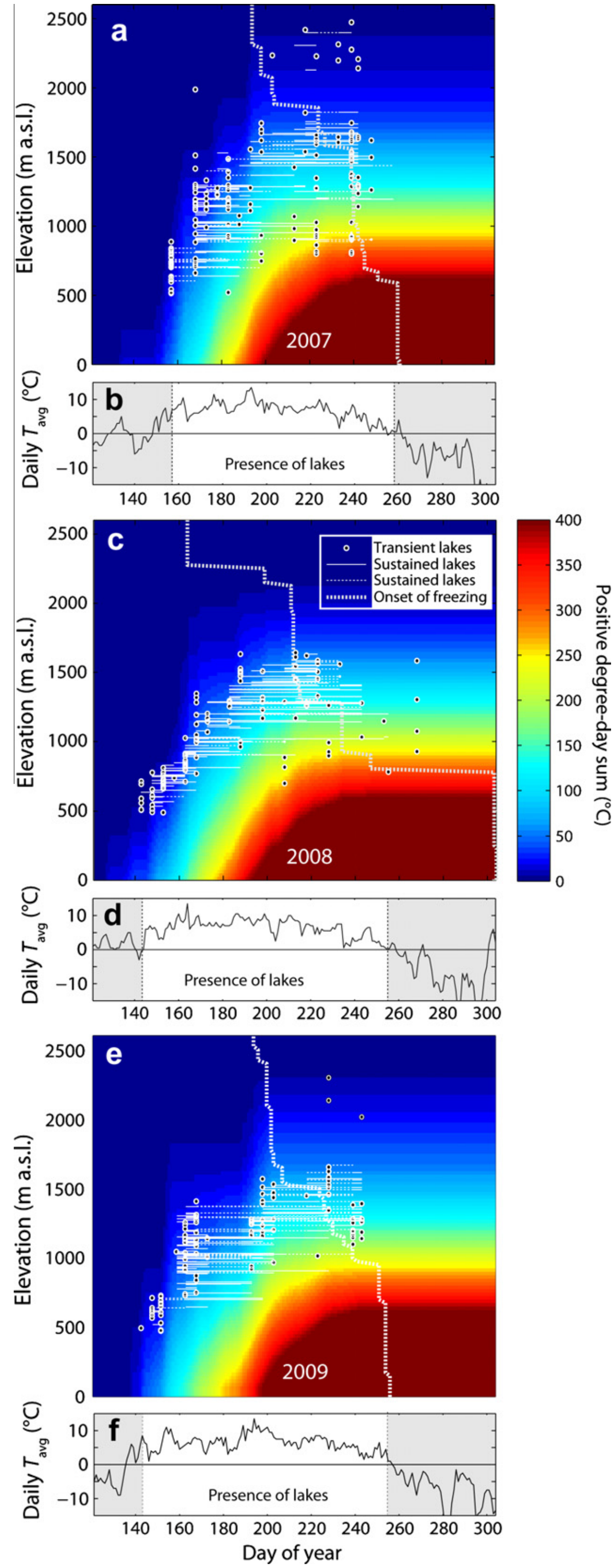

Fig. 2. Lake inception and cessation as a function of time and elevation in (a) 2007, (c) 2008 and (e) 2009, study area A1, Russell Glacier catchment, West-Greenland. Solid and dashed white lines mark the duration of individual sustained lakes. The dashed lines indicate periods where cloud cover prevent identification but where lakes are likely to exist. Transient lakes are indicated by white filled circles. The cumulative positive degree day field for each year is shown in the background and was calculated by correcting Kangerlussuaq temperature records, presented in (b) for 2007 (d) for 2008 and (f) for 2009 (see text for details). The dotted vertical white line indicates the onset of freezing at different elevations. Dotted vertical lines in panels (b), (d) and (f) indicate the first and last appearance of lakes.