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Evolution of supra-glacial lakes across the Greenland Ice Sheet

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ABSTRACT

We used 268 cloud-free Moderate-resolution Imaging Spectroradiometer (MODIS) images from 2003 and 2005–2007 to study the seasonal evolution of supra-glacial lakes in three different regions of the Greenland Ice Sheet. Lake area estimates were obtained by developing an automated classification method for their identification based on 250 m resolution MODIS surface reflectance observations. Widespread supra-glacial lake formation and drainage is observed across the ice sheet, with a 2–3 week delay in the evolution of total supra-glacial lake area in the northern areas compared to the south-west. The onset of lake growth varies by up to one month inter-annually, and lakes form and drain at progressively higher altitudes during the melt season. A positive correlation was found between the annual peak in total lake area and modelled annual runoff. High runoff and lake extent years are generally characterised by low accumulation and high melt season temperatures, and vice versa. Our results indicate that, in a future warmer climate [Meehl, G. A., Stocker, T. F., Collins W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J. & Zhao, Z. C. (2007). Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.], Greenland supra-glacial lakes can be expected to form at higher altitudes and over a longer time period than is presently the case, expanding the area and time period over which connections between the ice sheet surface and base may be established [Das, S., Joughin, M., Behn, M., Howat, I., King, M., Lizarralde, D., & Bhatia, M. (2008). Fracture propagation to the base of the Greenland Ice Sheet during supra-glacial lake drainage. *Science*, 5877, 778–781] with potential consequences for ice sheet discharge [Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J. & Steffen, K. (2002). Surface melt-induced acceleration of Greenland Ice Sheet flow. *Science*, 297, 218–221.].

1. Introduction

The Greenland Ice Sheet is thinning at low elevations due to a combination of increased surface melting and increased glacier discharge (Krabill et al., 2004; Rignot & Kanagaratnam, 2006; Hanna et al., 2008; Rignot et al., 2008). Recent observations along the western margin of the ice sheet have identified a correlation between surface melting and summer ice sheet acceleration, with summertime speedups at land-terminating margins of up to 100% relative to winter velocity (Zwally et al., 2002; Joughin et al., 2008; Van de Wal et al., 2008; Shepherd et al., 2009; Palmer et al., submitted for publication). Enhanced glacial sliding caused by the rapid delivery of surface melt-water to the ice–bedrock interface is suggested as a mechanism for the observed velocity increases (Zwally et al., 2002). A recent study by Das et al. (2008) demonstrated that rapid transfer of surface melt-water to the ice bed can occur through ~1 km of subfreezing ice initiated by water-driven fracture propagation evolving into moulin flow. Such hydraulic connections between the ice sheet surface and the base are not included in the ice sheet models which form the basis of the Intergovernmental Panel on Climate Change (IPCC) sea level projections (Meehl et al., 2007). Although attempts to incorporate the effect of increased surface melt-water on ice dynamics suggest that the IPCC predictions of future sea level rise may be underestimates (Parizek & Alley, 2004), the value of existing model projections remain uncertain due to our limited understanding of the link between ice sheet hydrology and ice motion.

During summer, supra-glacial lakes form in topographic depressions in the ablation zone of the Greenland Ice Sheet (e.g. Echelmeyer et al., 1991; Luthje et al., 2006; Box & Ski, 2007; McMillan et al., 2007; Sneed & Hamilton, 2007), and it is thought that the drainage of these lakes may play a key role in linking the surface melt signal to ice motion by supplying the volume of water needed to propagate crevasses to the base of the ice (Alley et al., 2005; Van der Veen, 2007; Das et al., 2008). Numerous lake drainage events have been identified on the ice sheet's western margin (Box & Ski, 2007), with lakes up to

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0.044 km^3 draining in less than 2 hours (Das et al., 2008). Although the maximum supra-glacial lake area, volume and depth do not always occur on the same day, positive correlations between supra-glacial lake area and volume, volume and maximum depth, and area and maximum depth have been identified (Box & Ski, 2007).

Although supra-glacial lakes occur across much of the ablation zone of the Greenland Ice Sheet, lake investigations have so far been limited to its western margin (Luthje et al., 2006; Box & Ski, 2007; McMillan et al., 2007; Das et al., 2008). Since factors like climate (temperature, snow accumulation, melting, etc.), topography and glacier discharge rates vary across Greenland (Ohmura & Reeh, 1991; Abdalati & Steffen, 2001; Rignot & Kanagaratnam, 2006), it is important to extend existing studies of seasonal changes in supra-glacial lake development to the remainder of the ice sheet to clarify the role that lakes may play in controlling the ice sheet response to changes in climate. In this study, we use Moderate-resolution Imaging Spectroradiometer (MODIS) imagery to investigate the temporal and spatial evolution of supra-glacial lake area in three climatically different regions of the Greenland Ice Sheet.

2. Study areas

Three areas located in the south-western, north-western, and north-eastern region of the Greenland Ice Sheet were selected for this study (Fig. 1). The areas represent different climate zones, the northern areas being characterised by a colder and drier climate than the south-western study area (Ohmura & Reeh, 1991; Abdalati & Steffen, 2001; Cappelen et al., 2001). Supra-glacial lakes tend to be smaller and less abundant in the south-eastern part of the Greenland Ice Sheet, so this region was not included in our study.

The south-western study area covers approximately 14 500 km^2 and extends from 66°39 to 67°56 N between the ice margin and ice at approximately 1700 m in elevation. The area comprises 10 major supra-glacial lake catchment basins including those overlying the

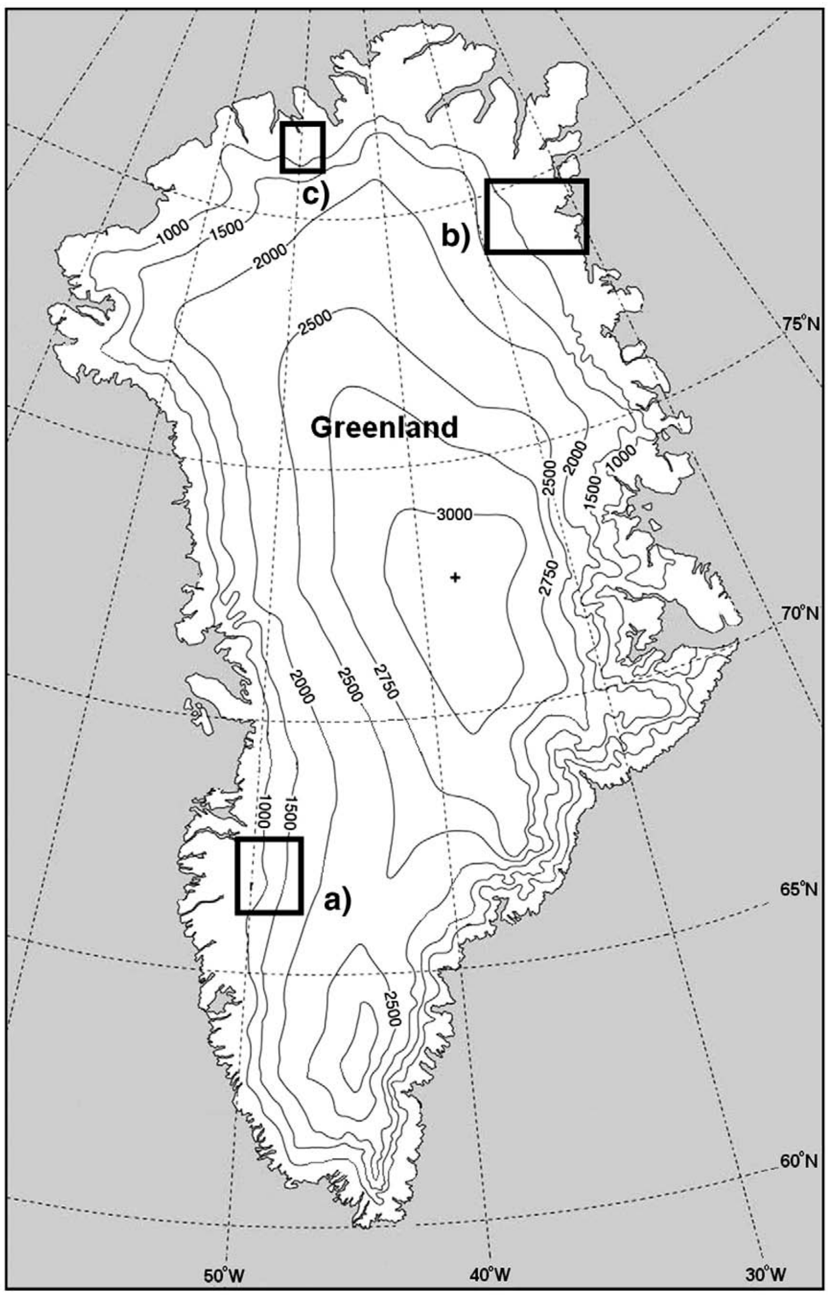

Fig. 1. a) The south-western Greenland study area including various catchments, b) the Nioghalvfjerdsbrae/Zachariae catchments, and c) the Ryder catchment.