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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 14500 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

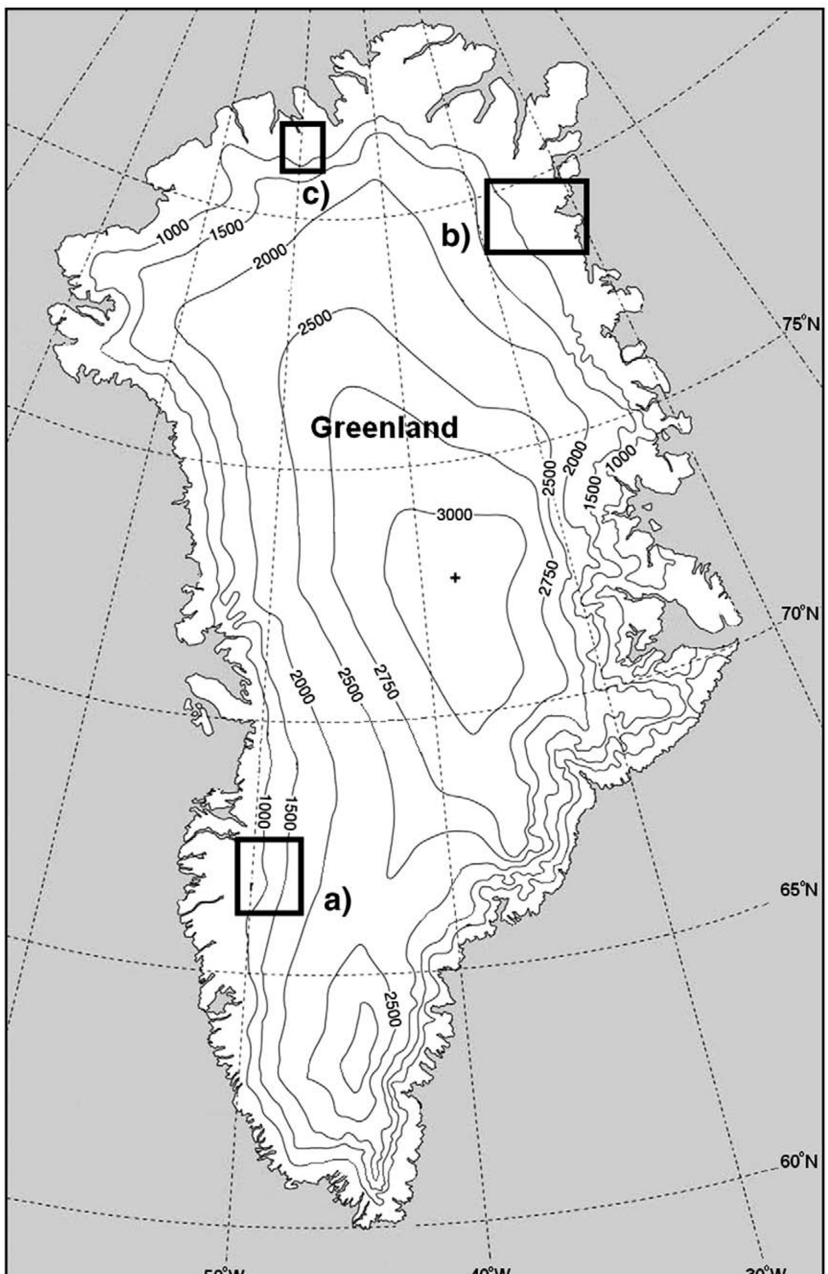

Fig. 1. a) The south-western Greenland study area including various catchments, b) the Nioghalvfjerdsbrae/Zachariae catchments, and c) the Ryder catchment.

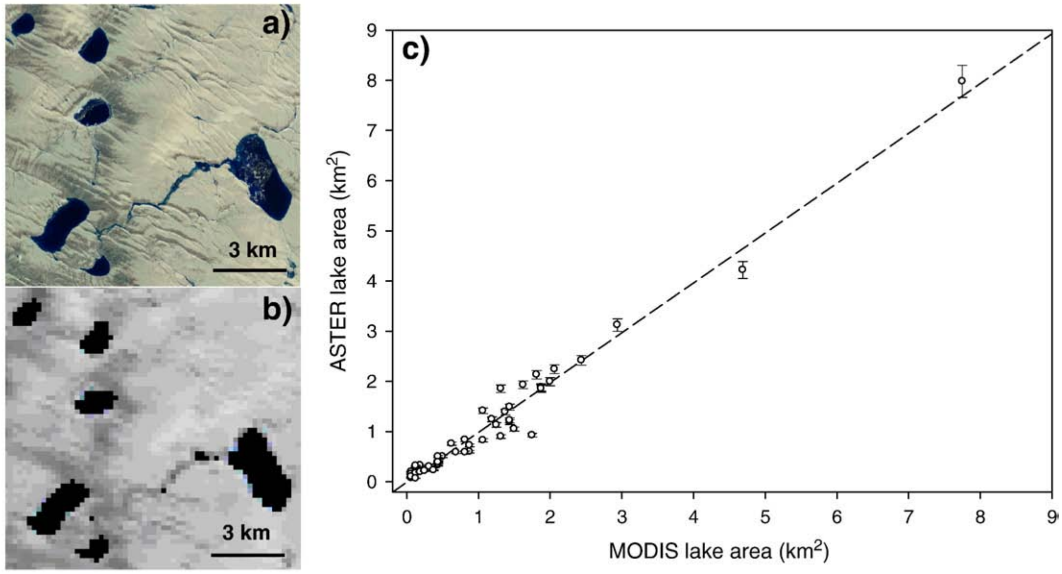

Fig. 2. a) A 15 m resolution ASTER image, b) a classified MODIS image where solid black colour represent areas classified as lakes), and c) the relationship between lake area estimates derived from manual digitising of a 15 m resolution ASTER image and the automated MODIS classification method ($r = 0.99$, RMSD = 0.22 km^2).

Isunguata Sermia and Russell glaciers (Palmer et al., submitted for publication). An InSAR-derived ice surface elevation model posted at 100 m and with an RMS vertical error of 18 m was recently developed for this region (Palmer et al., submitted for publication), and the availability of this high resolution elevation data determined the location and extent of this study area.

The north-eastern study area lies within the Nioghalvfjerdsbrae and Zachariae Isstrom drainage basins and covers approximately 17 500 km^2. It extends from 78°21 to 79°50 N and includes the area between the ice sheet margin and ice at approximately 1200 masl (meters above sea level). The north-western study area is located within the Ryder Glacier catchment and covers about 4100 km^2 between 80°45 –81°47' N and 48°19'–51°47' W. It comprises the area between the ice margin and ice at about 1200 m elevation.

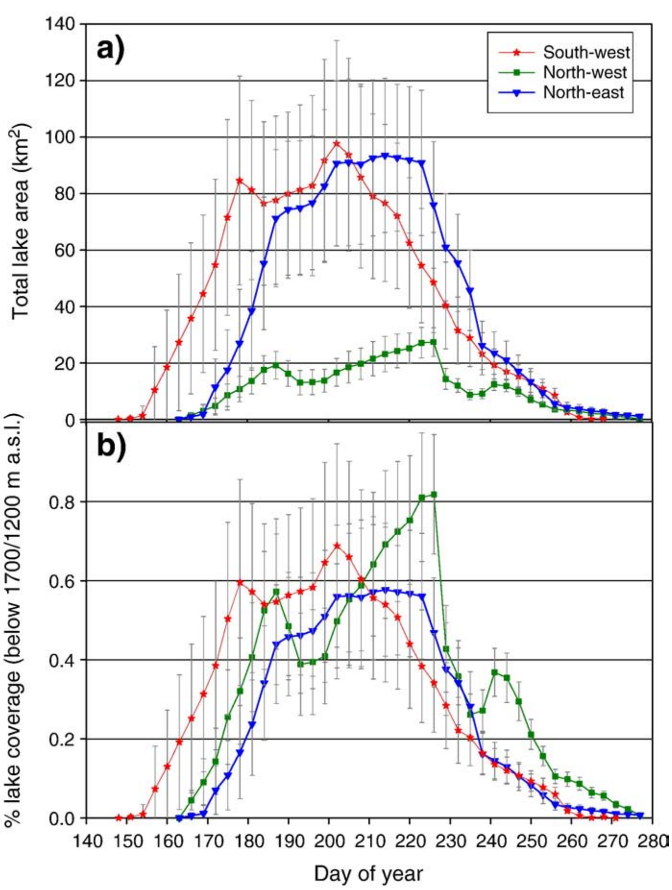

Fig. 3. The seasonal evolution in a) total area and b) fractional coverage of supra-glacial lakes averaged over 4 melt seasons (2003 and 2005–2007). The fractional lake coverage is calculated for the area below 1700 masl in the south-west and below 1200 masl in the north.

3. Data and methods

3.1. MODIS images and pre-processing

Cloud-free MODIS imagery from the 2003 and 2005–2007 melt seasons (May–October) were employed in this study. These melt seasons incorporate both high and medium runoff and melt extent years (Hanna et al., 2008). A total of 268 images were analysed, with the

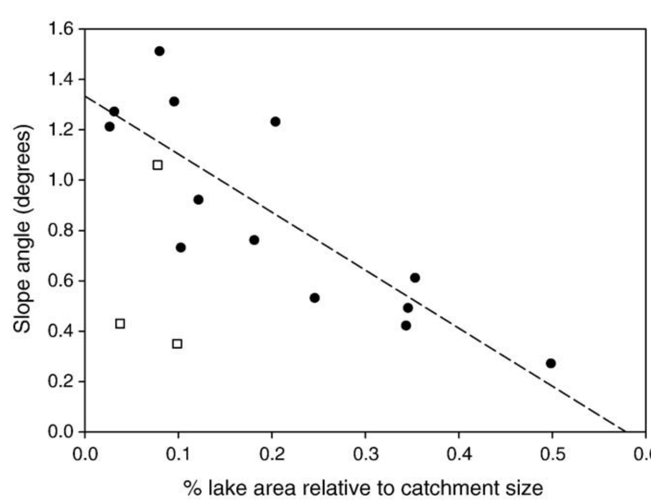

Fig. 4. Average slope angle versus percentage lake area relative to catchment size for each 200 m elevation band within the three study areas ($r = -0.84$). High elevation regions with little or no melt are not included in the regression analysis (squares).

number of images per season ranging from 14 to 35 at each location. The survey was based on MODIS data spanning the visible spectrum, i.e. band 1 (red; 0.62–0.67 μm), band 3 (blue; 0.46–0.48 μm), and band 4 (green; 0.54–0.57 μm). MODIS band 1 has a spatial resolution of 250 m, while the resolution of bands 3 and 4 is 500 m.

MODIS level 1 B Calibrated Radiances (MOD02) data were obtained from the Level 1 and Atmosphere Archive and Distribution System (LAADS) and processed according to the method outlined in Gumley et al. (2007). The MODIS Corrected Reflectance algorithm (CREFL) developed by Jacques Descloitres at NASA Goddard Space Flight Center, was used to correct for molecular (Rayleigh) scattering and gaseous absorption (water vapor and ozone) in the visible bands. A resolution-sharpening algorithm (Gumley et al., 2007) was used to re-project bands 3 and 4 data from 500 m to 250 m. The resolution-sharpening algorithm requires that bands 1, 3, and 4 at 500 m resolution are bi-linearly interpolated to the equivalent of 250 m resolution. The spatial resolution ratio from MODIS band 1 (band 1 at 500 m, interpolated to 250 m/band 1 at 250 m) was then computed and used to sharpen bands 3 and 4 data based on the assumption that the same spatial resolution difference exists for all three bands. The geolocation of the 250 m image data was based on the MODIS Geolocation product (MOD03) which stores latitude and longitude information at a horizontal resolution of 1000 m. To accurately re-project the 250 m image data, the geolocation data was interpolated to 250 m resolution by applying an interpolation algorithm to each earth scan (Gumley et al., 2007). The geolocation of the image data was performed using the MODIS Swath-to-Grid Toolbox (Haran et al., 2001).

3.2. Image classification

A classification method for determining supra-glacial lake area from MODIS reflectance images was developed using Definiens eCognition Professional 4.0 (Definiens, 2003). The classification was performed using fuzzy logic membership functions which enable classes to be assigned according to the membership degree rather than crisp threshold values (Baatz et al., 2004). The classification was based on MODIS band 1 (red) reflectance with 250 m native spatial

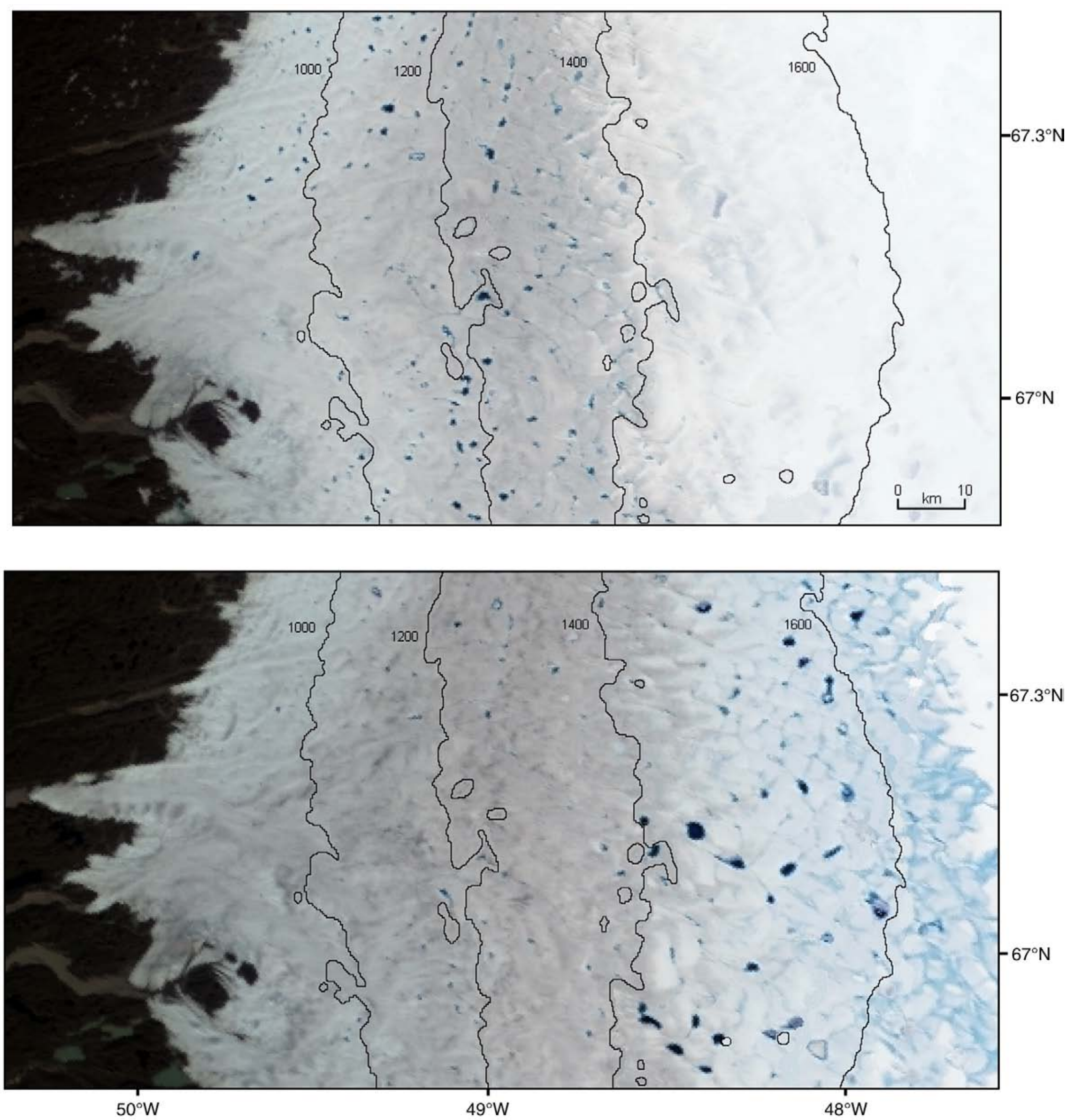

Fig. 5. MODIS true colour images showing the difference in supra-glacial lake location and size between day 162 (above) and 199 (below) in the southern part of the south-western study area during the 2003 melt season.

resolution and the ratio between band 3 (blue) and band 1 reflectances. The information in band 4 (green) was used for visual analysis, but not included in the image classification.

The classification accuracy was evaluated by comparing the MODIS classification result with a lake area dataset derived from 15 m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery. The ASTER scenes were acquired over the south-western study area on 1st August 2001, and bands spanning the visible spectrum were used to manually digitise the margins of 53 lakes of different shapes and sizes. Only ice-free lake areas were included in the ASTER reference dataset since the MODIS classification method is unable to distinguish between lake ice and the ice surrounding the lakes. To estimate the error of the digitised ASTER lake areas due to the 15 m resolution of the ASTER imagery, the case of a circular lake with an area equal to the mean of the 53 lakes was considered. The uncertainty associated with this area measurement was calculated to be 4%, and this error was applied to each lake area estimate derived from the ASTER imagery.

A comparison between the ASTER reference dataset and lake area estimates obtained from a classified MODIS image acquired on the same day as the ASTER imagery is presented in Fig. 2. The results show a strong, positive correlation between the two data sets ($r=0.99$). The total area of the 53 lakes derived from the MODIS classification method exceeded the corresponding area in the reference data by only 1.6% (56.7 and 57.6 km^2 for the ASTER and MODIS derived total lake areas, respectively). A root mean square deviation (RMSD) of 0.22 km^2 was calculated for the whole dataset. This value was multiplied by the number of lakes occurring in each image scene and applied as an error to the total lake area estimates.

Due to the coarse resolution of the MODIS imagery, lakes with an area smaller than approximately 0.1 km^2 were not included in the study. By measuring all lakes within a subset of the ASTER imagery, the smaller lakes were found to account for about 12% of the total lake area. However, the number of lakes with an area below 0.1 km^2 varies through the summer, with the highest number of smaller lakes occurring at the start of the melt season. Since the ASTER image used for the test was acquired at a later stage in the melt season, the percentage of unidentified lake area at the start of the summer is likely to be somewhat higher than 12%.

3.3. Modelled runoff, accumulation, and surface temperature

Runoff, accumulation and surface temperature data at 5×5 km spatial resolution for each of the three study areas were extracted from a monthly degree-day surface melt-water runoff and retention model (Hanna et al., 2005). This model has been adapted from the annual runoff and retention degree-day model (DDM) of Janssens & Huybrechts (2000). Input parameters to the monthly runoff and retention model are downscaled and corrected six-hourly surface air temperature and 12- and 36-hour forecast total (large-scale plus convective) precipitation from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hanna et al., 2005).

4. Results and discussion

We investigated the spatial variation in the seasonal evolution of supra-glacial lakes across the Greenland Ice Sheet by comparing total lake area estimates within the three study areas averaged over four melt seasons (Fig. 3). The results show that the evolution of total supra-glacial lake area in the north-eastern and north-western catchments is delayed by 2–3 weeks when compared to the south-western catchment, with the averaged total lake extent in the south-western, north-eastern, and north-western study area reaching a maximum on days 203 (21th July), 215 (3rd August), and 227 (15th August), respectively (Fig. 3a). While the maximum total lake area estimates for the south-western and north-eastern catchments are about three times larger than for the north-west, the fractional lake coverage of the three regions is comparable (Fig. 3b). Supra-glacial lakes form up to altitudes of approximately 1700 masl in the south-west and 1200 masl in the two northern areas, and so we calculated the fractional lake coverage for the area below these altitudes to provide a comparison of lake distribution between each study site. The maximum lake coverage for the south-western, north-western, and north-eastern study area is 0.68%, 0.81%, and 0.58%, respectively. The results suggest that, while the peak in fractional lake coverage is reached at an earlier stage in the warmer south-west Greenland climate, the extent of the fractional lake coverage is similar and hence likely to be governed by factors other than climate, such as the surface topography of the ice sheet, as observed in previous lakes studies (Luthje et al., 2006; Box & Ski, 2007; Sneed & Hamilton, 2007).

To investigate the influence of the ice sheet surface slope on supra-glacial lake formation, we calculated the average ice surface slope and percentage lake area relative to catchment size within adjacent 200 m elevation bands across the three study areas (Fig. 4). Excluding high elevation regions with little or no melt, a strong negative correlation is found between these two parameters ($r=-0.84$), indicating that areas with steeper slopes have reduced potential for supra-glacial ponding. This is presumably because backslopes, which promote lake formation (Nienow & Hubbard, 2005), are less likely to form in steeper areas and because the resulting faster ice flow increases the likelihood of fracturing and water drainage. The lack of lakes in the south-eastern part of the Greenland Ice Sheet is believed to be due to the steeper ice surface slopes in this region.

In order to investigate the altitudinal variation in the seasonal evolution of supra-glacial lakes, a comparison was made between the

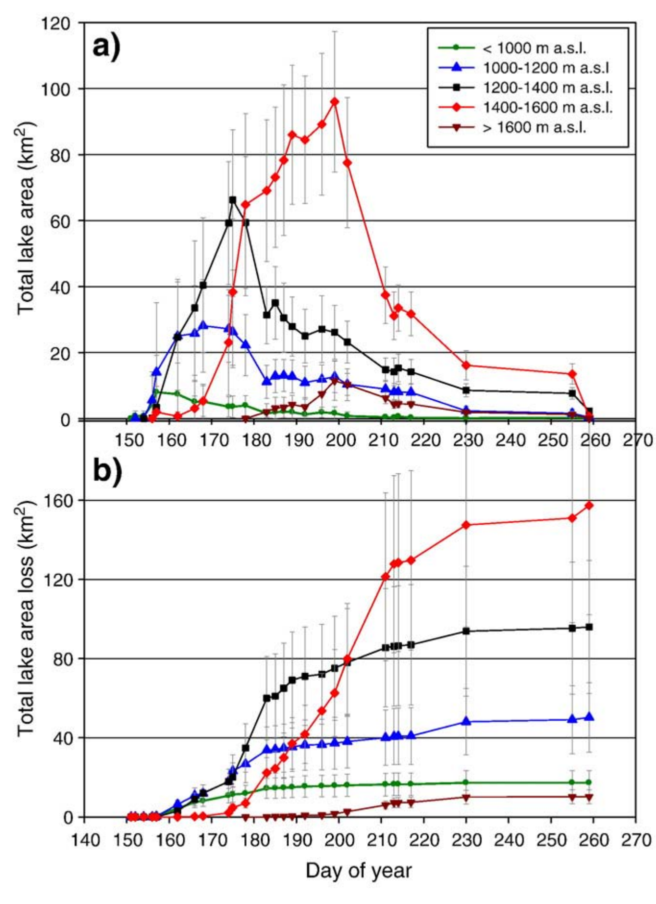

Fig. 6. a) Evolution in supra-glacial lake area according to elevation above sea level in the south-western study area during the 2003 melt season, b) cumulative plot of total lake area loss.

variation in total lake area within five discrete elevation bands (<1000, 1000–1200, 1200–1400, 1400–1600, and >1600 masl) in the south-western study area during the 2003 melt season. The results show a clear difference in the evolution of total lake area between the five zones, with lakes at lower elevations forming and draining earlier in the melt season than lakes located higher on the ice sheet (Figs. 5 and 6). The peak in total supra-glacial lake area within the five elevation bands occurred on days 157 (6th June), 168 (17th June), 175 (24th June), 199 (18th July), and 199 (18th July), respectively, and was followed by lake drainage (Fig. 6a). Within each elevation band, approximately one third of the total lake area loss occurred before the total lake area reached its maximum, indicating that both lake drainage and lake formation take place during the period of total lake area increase (Fig. 6b). Lakes forming at lower elevations are generally smaller than lakes located higher on the ice sheet, most likely due to the steeper ice sheet surface at lower elevations in the south-western study area (Fig. 5). On the day of maximum total lake extent, the average lake area within the five elevation bands was 0.16, 0.44, 0.68, 0.99, and 0.42 km^2 (from low to high elevation), respectively. The observed altitudinal variation in the evolution of supra-glacial lake area indicates that the pattern of lake drainage migrates inland throughout the melt season, providing the potential for hydraulic connections to be established between the surface and ice sheet bed across a wide sector of the ice sheet margin (Das et al., 2008).

Substantial inter-annual variations in the evolution of supra-glacial lake area are observed in all three study areas (Fig. 7). The onset of

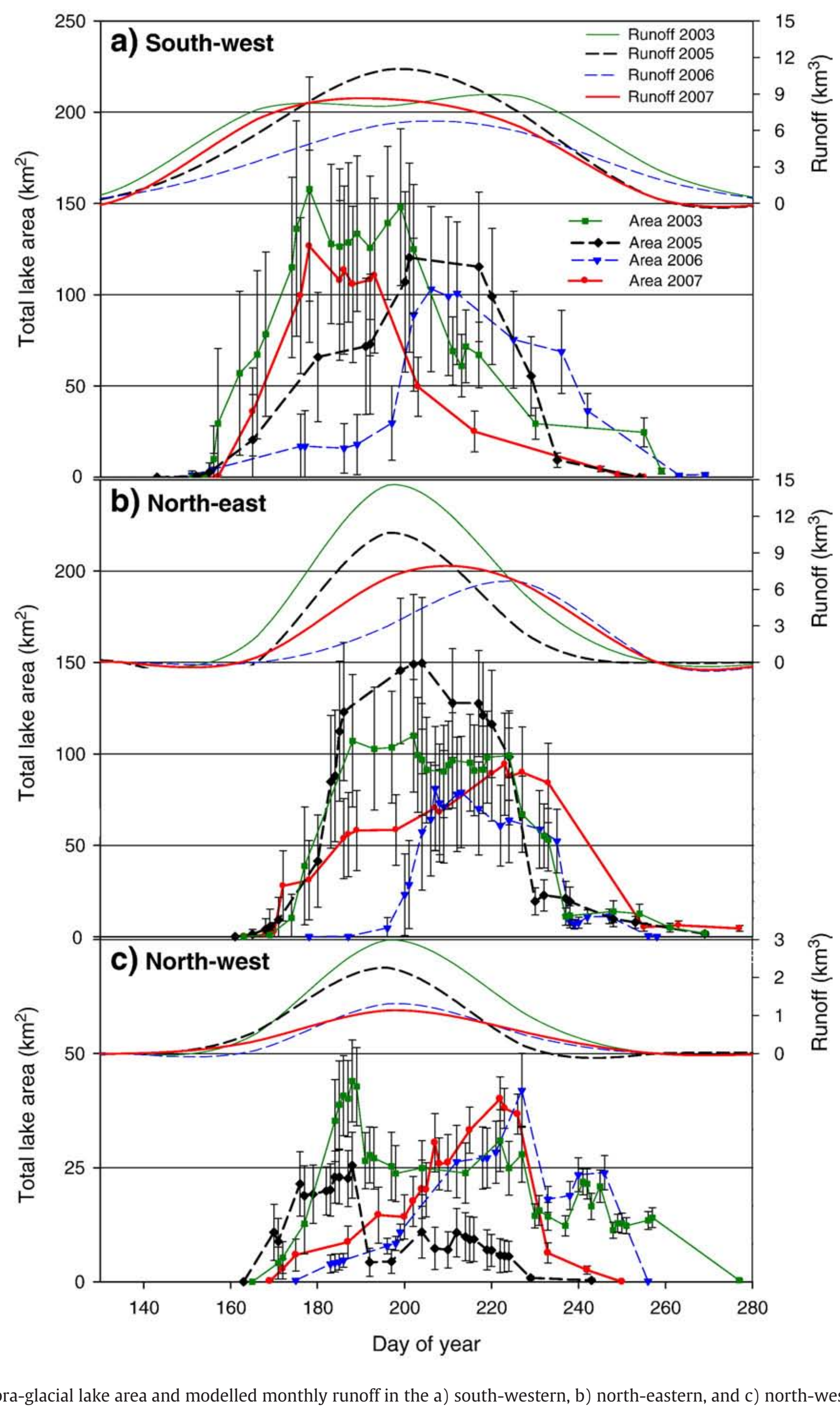

Fig. 7. Inter-annual variation in supra-glacial lake area and modelled monthly runoff in the a) south-western, b) north-eastern, and c) north-western study area. Note the different scale in c).

lake growth varies by up to one month between melt seasons, and similar variations are found for the timing of maximum total lake area (Table 1). The latest onset of lake formation occurs in 2006 in all the study areas, with rapid increases in supra-glacial lake extent starting around day 200 (18th July). The two northern study areas generally exhibit similar trends in seasonal lake area variations, with a late peak in maximum lake area in 2007 and early lake formation and maximum lake extent in 2003 and 2005 (Table 1). While comparable seasonal evolutions in total lake area are observed between the northern and south-western part of Greenland in 2003 and 2006, the timing of maximum total lake area in 2005 and 2007 differs between the northern and southern regions.

A comparison between the evolution in total melt-water extent and modelled monthly runoff values for the two northern areas shows that the late onset of lake growth observed in 2006 and 2007 correlates with low runoff in the first half of the melt seasons (Fig. 7b–c). The runoff varies less between seasons in the south-west as compared to the north, but a correlation between low runoff at the beginning of the 2006 melt season and a delayed onset of lake formation is evident also in the south-western study area (Fig. 7a). Our dataset indicates that, although similar regional trends in the evolution of supra-glacial lake area are observed in some years, an early onset of rapid lake formation in one region of the Greenland Ice Sheet is not necessarily consistent with an early and rapid melt signal elsewhere.

The maximum total lake area varies between seasons in all regions, with the peak occurring in 2005 in the north-east and in 2003 in the south-western and north-western study areas (Fig. 7a–c, and Table 1). The largest seasonal difference in peak total lake area was observed in the north-eastern region, where the peak lake extent was nearly 50% lower in 2006 compared to the previous year. An analysis of lake positions and lake areas in the 2005 and 2006 satellite imagery shows that the greater total lake area observed in 2005 was due to the formation of supra-glacial lakes at higher elevations of the ice sheet

Table 1
Runoff, accumulation, melt season temperature, the maximum seasonal total lake area and the corresponding day of maximum total lake extent for the three study areas.

Study area	Year	Day_{max}	$Area_{max}$ (km^2)	Annual runoff (km^3)	Annual accumulation anomaly rel. to 2002–2008 mean (km^3)[a]	Melt season temp anomaly rel. to 2002–2008 mean (°C)[b]
South-west	2002	–	–	26.8	−0.7	+0.8
	2003	178	157.8	28.4	−3.5	+0.5
	2004	–	–	23.6	+3.0	+0.3
	2005	201	120.3	23.8	+1.8	+0.1
	2006	206	103.1	18.3	+1.7	−0.1
	2007	178	126.6	20.8	−2.3	−0.7
	2008	–	–	16.2	−0.2	−1.4
	Mean			**22.6**	**8.3**	**−2.9**
North-east	2002	–	–	18.0	+0.4	+0.4
	2003	202	109.9	22.3	−1.9	+0.8
	2004	–	–	10.8	−1.3	−1.2
	2005	204	149.6	13.0	+0.8	−0.4
	2006	207	81.1	9.2	+3.1	−0.6
	2007	223	94.4	13.2	+0.2	−0.1
	2008	–	–	22.8	−1.0	+0.9
	Mean			**15.6**	**3.9**	**−1.6**
North-west	2002	–	–	3.44	−0.26	+0.1
	2003	188	44.0	4.40	−0.18	+1.0
	2004	–	–	2.75	−0.20	−0.3
	2005	188	25.5	2.91	+0.05	−0.2
	2006	227	41.9	1.89	+0.24	−0.7
	2007	222	40.1	2.02	+0.28	−0.4
	2008	–	–	3.65	−0.05	+0.7
	Mean			**3.00**	**0.44**	**−2.5**

[a] The annual accumulation was calculated from September to August; e.g. annual accumulation 2003 = accumulation September 2002–August 2003.
[b] Melt season temperature = May–September in the South-west; June–August in the North-east and North-west.

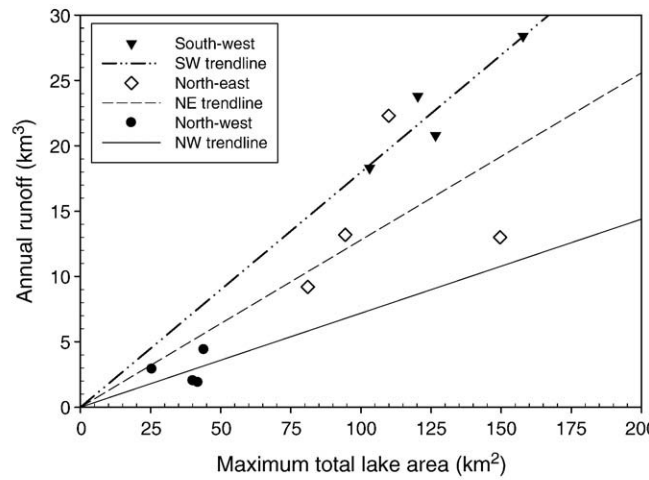

Fig. 8. Maximum total lake area and annual runoff for the three study areas.

(>~800 masl) where no lakes developed in 2006. Lakes also formed at higher altitudes in the 2003 and 2007 melt seasons, but these lakes were smaller than the ones observed in the 2005 imagery.

We investigated the extent to which supra-glacial lake area is correlated with the degree of runoff within each catchment by comparing the seasonal maxima in total lake area to modelled annual estimates of runoff (Fig. 8, Table 1). The results show a positive correlation between the two datasets, suggesting that local runoff influences seasonal variations in total supra-glacial lake extent. To investigate the factors driving the observed inter-annual variations in runoff and lake area, modelled annual accumulation and melt season temperature anomalies (relative to 2002–2008 mean) for each of the study areas were compared to the runoff and lake extent datasets (Table 1). High runoff and lake extent years (e.g. 2003) are generally synchronous with years of low accumulation and high melt season temperatures, while low runoff and lake extent years (e.g. 2006) generally correlate with years of increased accumulation and melt season temperatures below the average. Increased accumulation is believed to reduce net runoff since larger volumes of melt-water are retained in the thicker snowpack and more accumulation results in a higher albedo for a longer time, which reduces absorbed energy available for melt (Hanna et al., 2008). The combinations of high accumulation and high melt season temperatures or low accumulation and low melt season temperatures generally correlate with medium runoff and lake extent years (Table 1).

5. Conclusion

We used 268 MODIS images from the 2003 and 2005–2007 melt seasons to investigate the seasonal evolution of supra-glacial lakes in three different regions of the Greenland Ice Sheet. Lake area estimates were obtained by developing and applying an automated classification method to 250 m resolution MODIS imagery.

Our data reveal widespread supra-glacial lake formation and drainage across the Greenland Ice Sheet, with a 2–3 week delay in the evolution of total supra-glacial lake area in the northern study areas compared to the south-western study area. Lakes form and drain at progressively higher altitudes during the melt season, and the onset of lake growth varies by up to one month inter-annually. 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 data indicate that, in a future warmer climate (Meehl et al., 2007), supra-glacial lakes on the surface of the Greenland Ice Sheet can be expected to form earlier in the melt season and at higher altitudes than is presently the case. As a consequence, the area and time period over which connections between the ice sheet surface and base may be established (Das et al., 2008) will increase, potentially increasing the rate of ice sheet discharge and its sea level contribution (Zwally et al., 2002).

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