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Brief Communication
"Expansion of meltwater lakes on the Greenland Ice Sheet"

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Abstract. Forty years of satellite imagery reveal that meltwater lakes on the margin of the Greenland Ice Sheet have expanded substantially inland to higher elevations with warming. These lakes are important because they provide a mechanism for bringing water to the ice bed, causing sliding. Inland expansion of lakes could accelerate ice flow by bringing water to previously frozen bed, potentially increasing future rates of mass loss. Increasing lake elevations closely follow the rise of the mass balance equilibrium line over much of the ice sheet, suggesting no physical limit on lake expansion. Data are not yet available to detect a corresponding change in ice flow, and the potential effects of lake expansion on ice sheet dynamics are not included in ice sheet models.

Expansion of meltwater lakes on the Greenland Ice Sheet

Seasonal melting of the surface of the Greenland Ice Sheet creates large volumes of meltwater. At low elevations, where melting is fastest and the surface is bare ice or a thin layer of firn, meltwater runoff collects in surface depressions to form supraglacial lakes. Tens to hundreds of thousands of these lakes dot the periphery of the ice sheet, covering the zone of bare ice and extending through elevations where the firn layer is seasonally saturated (i.e., the wet snow zone). Above this elevation, meltwater production is low enough, and the firn layer thick enough, that all meltwater permeates into the firn rather than collecting on the surface. Lakes influence the dynamics of the ice sheet, because they provide a mechanism by which water can penetrate to the bed through hydraulic fracturing (Das et al., 2008), raising basal water pressures and causing the ice to "slide" along the ice/bed interface. Sliding causes the ice to flow faster, speeding the transport of ice toward lower elevations and, potentially, increasing the rate at which the ice sheet will lose mass under climate warming (Zwally et al., 2002).

In areas that already undergo lake formation and penetration of water to the bed, additional meltwater should not substantially impact ice flow on annual timescales. This is because the relationship between meltwater production and ice motion is not proportional, but instead forms a hysteresis caused by the evolving efficiency of the subglacial drainage system as water is added (Schoof, 2010) . However, if warming causes lakes to form at higher elevations, water may reach areas of previously frozen bed, increasing the speed and annual flux of ice to the margin. Increased penetration of meltwater would also heat the ice, reducing its effective viscosity and potentially increasing its flow speed (Phillips et al., 2010). Such processes are not yet included in prognostic ice sheet models.

The Greenland Ice Sheet has warmed substantially over the past two decades (Box et al., 2009; van den Broeke et al., 2009), lowering the surface mass balance and raising the elevation at which ablation equals the snow accumulation (i.e., the equilibrium line altitude, or ELA). Therefore, if lake formation is dependent only on meltwater volume and firn layer thickness, we would expect lakes to form at correspondingly higher elevations. Previous work has shown that the distribution of lake surface area does shift to higher elevations in warmer years (Liang et al., 2012). However, a lack of surface undulations on thicker ice may prevent lakes from forming further inland. Thus it is unclear whether the zone of lake formation itself can expand higher under warming.

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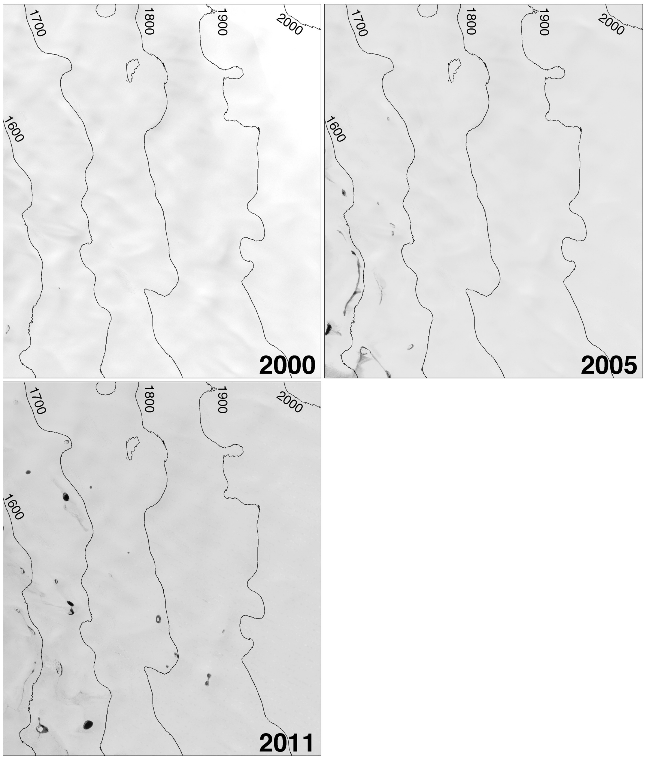

Fig. 1. Examples of stretched Landsat 7 ETM+ images used to detect lakes from the region above Jakobshavn Isbrœ (region E in Fig. 2). Open water appears as dark patches. Elevation contours are overlain at 100 m intervals. The region extends 54 km in the east–west direction and 63 km in the north–south direction. The images were obtained on 5 August 2000, 5 August 2005 and 13 August 2011.

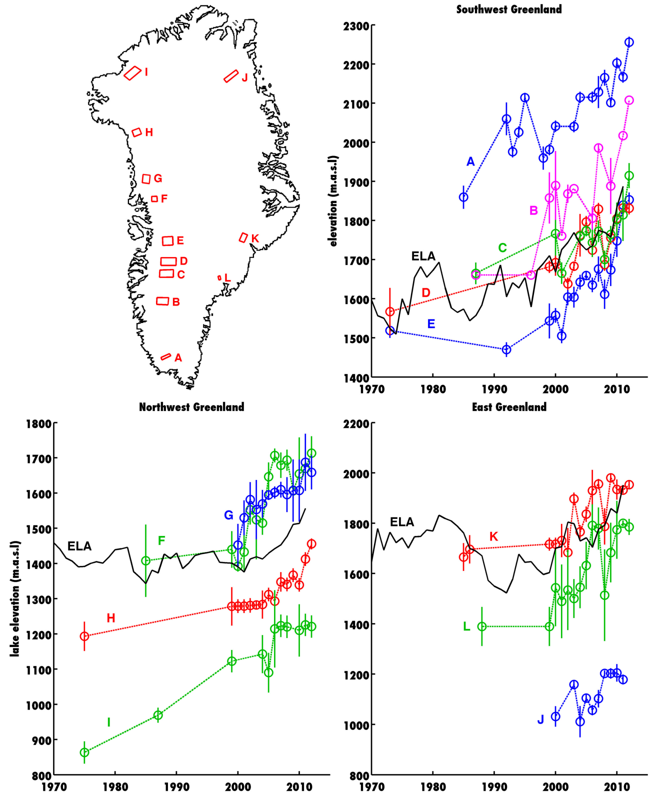

Fig. 2. Elevation of upper 0.1 km^2 of lake area within each study area labeled A–L. Error bars result from the ±0.05 uncertainty in normalized radiance threshold for lake classification. Black curves are the average equilibrium line altitudes (ELA) for those regions smoothed with a 5-yr retrospective mean. ELA values are extracted from the Regional Atmospheric Climate Model version 2 (RACMO2) (van Angelen et al., 2012).

To determine whether lakes are forming at higher elevations, we examined high-resolution satellite imagery spanning nearly four decades. The contrast in albedo between ice and water makes supraglacial lakes easily detectable in panchromatic band imagery with automated, statistical classification procedures (Liang et al., 2012). We mapped the annual distribution of lakes in 12 study regions around the ice sheet between 1972 and 2012 using all available imagery from several different sensors for the months of July and August. We primarily utilized visible band data from the Landsat series of satellites, including the Multi-Spectral Scanner (60-m resolution, 1972–1984), Thematic Mapper (30-m resolution, 1984 to present) and Enhanced Thematic Mapper-Plus (1999 to present, 15-m resolution). Landsat data were acquired from the US Geological Survey (http://glovis.usgs.gov/). Additionally, we used 15-m band-1 data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the Terra satellite, launched in 1999, acquired from the Land Process Distributed Active Archive (LPDAAC, https://lpdaac.usgs.gov/), and 5-m SPOT-5 imagery acquired in 2007 and 2008 and provided by the Stereoscopic survey of Polar Ice: reference Images and Topographies (SPIRIT) program (Korona et al., 2009). All imagery was orthorectified by the data providers prior to distribution. Useable images were interpolated to a common reference grid in a polar stereographic projection and cropped to the regions of interest. Our analysis utilized a total of 402 individual scenes from 244 satellite passes over our regions of interest. Pixel elevations were extracted from a 30-m digital elevation model (http://bprc.osu.edu/GDG/gimpdem.php).

To classify pixels as surface water within each image, we employ the methodology of Liang et al. (2012), where a radiance value threshold is determined from the slope of the negative tail in the normalized image histogram. Since our regions of interest are small (tens of km across) and are only over the interior ice sheet, we use the normalized radiance rather than the reflectance difference within a moving window employed by Liang et al. (2012). As in that study, we use a histogram slope threshold of 0.01, so that all pixels with radiance values below that point on the histogram are classified as lakes. A major benefit of this method is that the threshold of each image is calculated independently, so that no normalization between images is needed. Following automated classification, each lake map is quality checked by a visual comparison to the source image, which is exponentially stretched to enhance the contrast between water and ice (Fig. 1). In a few cases, the automated procedure resulted in misclassification and the threshold was slightly adjusted to provide a more consistent classification with other images.

The dominant source of error in the lake area classification is uncertainty of the radiance threshold, as determined by histogram slope. Through inspection of many images, we found that adjusting the normalized radiance threshold by ± 0.05 resulted in visually detectable classification errors. We therefore use this range to estimate the uncertainty in our lake area measurements.

Individual lakes may form and drain rapidly over the course of a melt season. We therefore must assess the potential effect of temporal sampling on our results. Johansson et al. (2013) found that lakes at high elevations typically appear for 20–30 days, peaking in early August, with a large degree of variability between years. When available, we chose multiple scenes in both July and August of each year, combining the resulting maps to obtain a single map of maximum lake extent. We further tested any dependency of our results on sampling date by calculating the correlation between the day of acquisition and (i) acquisition year and (ii) maximum lake extent. In no case was the correlation significant at the 95 % level, with average p values of 0.58 and 0.63 for (i) and (ii), respectively. Thus, while we cannot rule out that sampling interval influenced our results to some degree, the overall pattern from many time series is likely robust.

Figure 2 shows the elevation of the uppermost 0.1 km^2 of lake area for each study area grouped by region, which follows the edge of lake extent while providing some spatial and temporal smoothing. We also calculated the elevations for the uppermost 0.05 and 0.2 km^2 lake areas, but varying this parameter only shifts the curves, respectively, up and down, without substantially changing temporal variability. For areas with data in the 1970s and 1980s, we observe little change in lake elevation before the year 2000. Since 2000, however, all study areas have undergone an increase in lake elevation on the order of hundreds of meters and tens of km inland. Among the largest observed change is above the outlet glacier Jakobshavn Isbrœ (area E in Fig. 2), where lakes now extend to near 1900 m, approximately 30 km further inland than before 2000 (Figs. 1 and 2). Areas to the south now have lakes extending well above 2000 m elevation.

In the absence of a physical limit on lake extent, we would expect increases in lake elevation to match increases in the ELA throughout the record. This appears to be the case in the southwest and most of the northwest (Fig. 2) where, during the past few years, both lakes and the ELA have climbed to their highest observed elevations. This pattern is less clear in East Greenland and above Humboldt Glacier (area I) in the far northwest where, after rising steeply early in the decade, lake elevations have not kept pace with the continued rise in the ELA over the past several years. The eastern Greenland margin is several times steeper than its western counterpart and has a larger gradient in surface mass balance, potentially causing a longer lag time between rising of the ELA and thinning of the firn layer to allow lake formation. If this is the case, and the ELA remains elevated or rises further, we would expect lakes to continue to expand in those regions in the future as the firn layer thins and becomes saturated.

While these results confirm the substantial inland expansion of meltwater lakes on the ice sheet over the past decade, data are not yet available to investigate a corresponding change in ice dynamics. High accumulation rates in the interior hamper space-based measurements of ice flow speed, and those data are generally restricted to the winter months (e.g., Joughin et al., 2010). Ground-based GPS measurements are the only current means of detecting such a change, but these data are lacking. These results point to how little is known about the response of the interior ice sheet to widespread forcing at its margin.

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