The Cryosphere Discuss., 6, 4447–4454, 2012
www.the-cryosphere-discuss.net/6/4447/2012/
doi:10.5194/tcd-6-4447-2012

The Cryosphere
Discussions

Brief Communication
"Expansion of meltwater lakes on the Greenland ice sheet"

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Received: 4 October 2012 – Accepted: 10 October 2012 – Published: 16 October 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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, warming the ice and 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 in West Greenland closely follow the rise of the mass balance equilibrium line, suggesting no physical limit on lake expansion there. This is 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 the surface is bare ice and melting is fastest, meltwater collects in surface depressions to form supraglacial lakes. Thousands of these lakes dot the periphery of the ice sheet, extending from the margin to elevations where seasonal meltwater runoff is less than annual snow accumulation. There, meltwater infiltrates into the permeable firn layer rather than collecting on the surface. Lakes are important to 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), warming the ice and causing it to “slide” along the ice/bed interface. Both ice warming and sliding cause 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. This would impart heat to the ice, lowering its viscosity, and causing basal sliding, increasing the speed and annual flux of ice to the margin. Such a processes is not yet included in prognostic ice sheet models.

The Greenland Ice Sheet has warmed substantially over the past two decades (van den Broeke et al., 2009), lowering the surface mass balance and raising the elevation at which meltwater runoff equals the snow accumulation (i.e. the Equilibrium Line Altitude, or ELA). Therefore, if lake formation is only dependent 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 higher within the zone of bare ice 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.

To determine whether lakes are forming at higher elevations, we examined high-resolution satellite data spanning nearly four decades. The contrast in albedo between ice and water makes supraglacial lakes easily detectable in panchromatic band imagery using semi-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 from the Land Process Distributed Active Archive (LPDAAC, http://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 orthorectifed by the data providers prior to distribution. Useable images were interpolated to a common reference grid in a polar stereographic projection and cropped to regions of interest.

To enhance open water relative to the snow and ice background, the reflectance scale of each image was inverted and stretched exponentially (Fig. 1). Following the methodology in Liang et al. (2012), pixels are then classified as water using a threshold based on the slope of the positive tail in the image histogram. Each lake map is then manually quality checked and the pixel threshold is adjusted if needed. All maps within a melt season are combined to provide one map of maximum lake extent for each year with data. Elevations of pixels classified as water were extracted from a 30-m digital elevation model (http://bprc.osu.edu/GDG/gimpdem.php).

Figure 2 shows the change in the mean 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. Adjusting this area threshold changes the absolute elevations but not the temporal change substantially. For areas with data in the 1970's and 1980's, little change in lake elevation is observed 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 10's 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. In East Greenland and above Humboldt Glacier (area I) in the far northwest, however, lake elevations have not kept pace with the rise in the ELA, suggesting a physical limit. 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.

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 Global Positioning System measurements are the only current means of detecting such a change, but such 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.

Acknowledgements. This work was funded by grants NNX11AR47G and NNX10AN61G to I. M. Howat from the US National Aeronautics and Space Administration.

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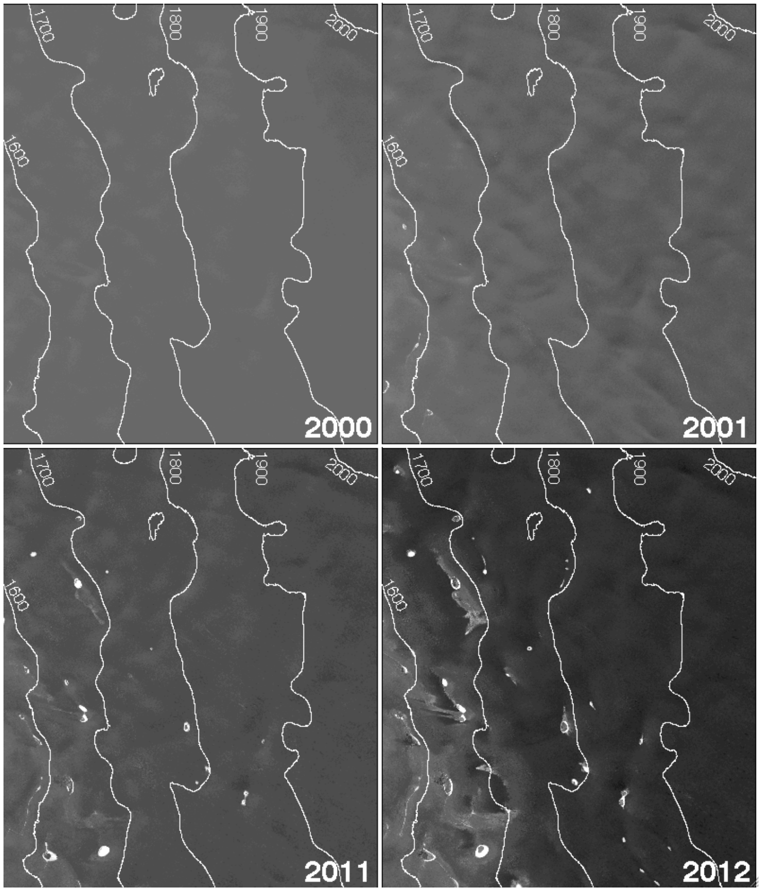

Fig. 1. Examples of inverted and stretched August Landsat 7 ETM + images from four different summers used to detect lakes from the region aboe Jakobshavn Isbrœ (region E in Fig. 2). Open water appears as bright patches. Elevation contours are overlain at 100 m intervals. The region extends 54 km in the east-west direction and 63 km in the north-south direction.

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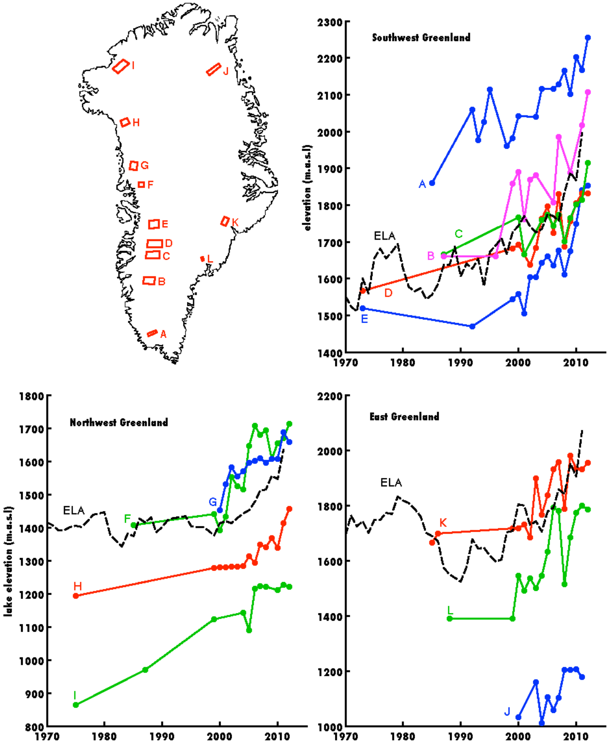

Fig. 2. Changes in elevation of upper 0.1 km^2 of lake area within each study area labeled A-L. Black dashes are the average Equilibrium Line Altitudes (ELA) for those regions smoothed with a 5-yr running mean. ELA values are extracted from the Regional Atmospheric Climate Model version 2 (RACMO2) (Angelen et al., 2012).