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Characterizing supraglacial lake drainage and freezing on the Greenland Ice Sheet

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Abstract

The behaviour of supraglacial lakes on the Greenland Ice Sheet has attracted a great deal of focus, specifically with regard to their fast drainage through hydrofracturing to the ice sheet base. However, a previous study has shown that this mode of drainage accounts for only 13 % of the lakes on the Greenland Ice Sheet. No published work to date has studied what happens to those lakes that do not drain suddenly. We present here three possible modes by which lakes can disappear from the ice sheet, which will have strongly contrasting effects on glacial dynamics and the ice sheet water budget. Around half of all supraglacial lakes observed persisted through the melt season and froze at the end of summer. A third drained slowly, which we interpret to be a result of incision of the supraglacial lake exit-channel. The fate of 7 % of lakes could not be observed due to cloud cover, and the remainder drained suddenly. Both fast and slow lake drainage types are absent at higher elevations where lakes tend to freeze despite having similar or longer life spans to lakes at lower elevations, suggesting the mechanisms of drainage are inhibited. Groups of neighbouring lakes were observed to drain suddenly on the same day suggesting a common trigger mechanism for drainage initiation. We find that great care must be taken when interpreting remotely sensed observations of lake drainage, as fast and slow lake drainage can easily be confused if the temporal resolution used is too coarse.

1 Introduction

Supraglacial lakes form around the margin of the Greenland Ice Sheet, developing in most regions where surface melt occurs in the summer months. Lake formation can occur on both bare ice and firn (Echelmeyer et al., 1991). The locations of the depressions in which lakes form appear to be controlled by bedrock topography, and therefore lakes remain in the same positions from year-to-year rather than advecting with ice flow (Echelmeyer et al., 1991; Selmes et al., 2011).

The drainage of supraglacial lakes in Greenland was first noted by Thomsen et al. (1989), who observed their tendency to empty periodically. Moulins were found in the centre of these lake sites suggesting drainage through the ice rather than supraglacially. The sudden drainage of a supraglacial lake was instrumented by Das et al. (2008), who found that drainage occurred in < 24 h temporarily reducing basal drag and increasing sliding locally, presumably as a result of pressurized water at the ice-bed interface. Passive seismic observations made by Das et al. (2008) are in keeping with the theory that this sudden lake drainage occurs through the propagation of existing crevasses by hydrofracture (Alley et al., 2005). These findings are supported by further field observations from Doyle et al. (2013), who recorded the drainage of a large lake (4 km^2) through hydrofracture in approximately two hours.

While the immediate dynamic effects of lake drainages appear to be localized, Zwally et al. (2002) observed longer-term surface-melt-related velocity changes in SW Greenland. Similar observations have also been made across larger areas of SW Greenland (Joughin et al., 2008). Lake drainage through hydrofracture is unlikely to be the direct cause of this acceleration owing to the localized nature of the speedup associated with lake drainage. However, the conduits produced during drainage events link the surface and basal hydrological systems allowing further meltwater to reach the bed (Das et al., 2008).

However recent studies have shown that the dynamic effect of surface meltwater forcing may be limited to the early part of the melt season when the basal hydrological network is more inefficient (Schoof, 2010). Once the subglacial network becomes more efficient, high meltwater discharges no longer affect ice-sheet velocity. Paradoxically this phenomenon may mean that annual mean velocity is lower in high melt than low melt years (Sundal et al., 2009). Despite this, the pressurised pulses of water provided by sudden lake drainage may still be able to overwhelm the subglacial hydrological system and cause increases in ice motion (Schoof, 2010).

To date, studies of the fate of supraglacial lakes on the Greenland Ice Sheet have focussed on those lakes which drain suddenly (Box and Ski, 2007; Das et al., 2008),

despite these lakes only accounting for $\sim 13\,\%$ of the total population of Greenland supraglacial lakes (Selmes et al., 2011). The fate of the remaining $\sim 87\,\%$ of lakes is poorly understood. Liestøl et al. (1980) describe a lake on Finsterwalderbreen, Svalbard, draining through the incision of the exit channel allowing supraglacial drainage; this process has not been reported on the Greenland Ice Sheet but it seems reasonable to assume that it does occur.

We monitored the changing surface area of 2600 lakes over a five-year period from 2005–2009 using 3704 MODIS images. Our objectives were to develop a high temporal resolution record of all large lakes in Greenland, determine what happens to those lakes that do not drain suddenly as well as those that do, and to see if the drainage behaviour of lakes as observed remotely can reveal more about why some lakes drain suddenly and others do not. Our aim was to provide insight into the behaviour of lakes that do not drain suddenly, and thus infer what role they may play in the hydrological and dynamic systems of the Greenland Ice Sheet.

2 Methods

We have used the dataset of lake areas for the period 2005–2009 described in Selmes et al. (2011), and added methods for studying and ultimately classifying the behaviour of those lakes that do not drain suddenly in the manner described in that paper.

2.1 Data selection

The process of monitoring lake drainage requires both fine enough spatial resolution to be able to distinguish changes in lake area, considerable swath width to image the whole ice sheet, and rapid repeat imagery to determine the period of time in which lake drainage has occurred. MODIS imagery provides a good compromise between adequate spatial resolution (250 m), wide swath (2330 km) and sub-daily re-imagining as a result of converging orbits in high latitudes and the aforementioned swath. While the 250 m pixel size means that some lakes will not have been recorded, it has been estimated that 98 % of lake volume in SW Greenland is contained in lakes visible in MODIS imagery (Krawczynski et al., 2009).

We used MODIS data for the purposes of this study. The MODIS sensors are moderate spatial resolution, wide swath multispectral instruments on board the Terra and Aqua satellites. Owing to the number of images available, only data from Terra were needed. We used MODIS band 1 (620–670 nm) for lake classification as this wavelength gives the greatest difference in reflectance between ice and water of any MODIS band, and these data are available at 250 m without requiring spectral sharpening techniques.

Our observations covered the melt seasons of the observation period, specifically the part of each year between days 140–280 (mid May–late October). This period included a record melt year in Greenland (2007, Mote, 2007), and record melt year for the north of the GrIS (2008, Tedesco, 2008), as well as two low melt years (2006 and 2009, Mote, 2007; Box et al., 2012). While much of the ice sheet has 24 h solar illumination during the Arctic summer, low solar angles cause shadowing that make classification problematic in complex topography. To counter this shadowing, we used images from the period 13:00–16:00 UTC, a time range including local midday (14:00 UTC).

These criteria resulted in 250–350 images per summer through the period studied. Several images of each point on the ice sheet per day were usually included which allowed imaging around drifting cloud. Using this method 80–92 cloud-free days could be imaged out of the 140 in our observation period each year, with more cloud-free days in the north than the south (Selmes et al., 2011, Supplement).

2.2 Preprocessing

All images were transformed onto a common grid in a polar stereographic projection. The geolocation process was carried out using the MODIS Reprojection Tool (Swath) developed by the Land Processes Distributed Active Archive (https://lpdaac.usgs.gov/tools/modis_reprojection_tool_swath). This tool also removed "bow-tie" distortions that

resulted from the increase in ground resolution away from nadir causing data duplication. MODIS Level 1B radiance data were converted to reflectance using the Corrected Reflectance Science Processing Algorithm developed by the Goddard Space Flight Center (http://directreadout.sci.gsfc.nasa.gov). This algorithm performs a basic atmospheric correction which accounts for Rayleigh scattering and absorption by atmospheric water and ozone.

To simplify the later classification of images, we applied manually digitized land/ice mask to remove pixels containing coastal bedrock and nunataks. Clouds were masked out by thresholding coincident MODIS thermal data: pixels with < 0.06 band 7 reflectance were assumed to be cloud contaminated. This threshold was chosen experimentally (Selmes et al., 2011).

2.3 Lake classification

We converted MODIS band 1 reflectance into a binary classification of water/surrounding ice by comparing the reflectance of each pixel to that of the surrounding pixels in a 21×21 window. Pixels with a reflectance of < 65 % of the reflectance of the surrounding pixels were classified as water: a threshold chosen experimentally by comparing the areas of lakes obtained from a supervised classification of coincident ASTER data which has a higher spatial resolution than MODIS (15 m). This approach removed the need for different reflectance thresholds as the reflectance of the ice sheet changed throughout each melt season (Selmes et al., 2011). It was sometimes difficult to avoid false positives caused by wet ice and shadowing. We significantly reduced errors of commission by initially locating the lakes using classifications of ~ 30 images per year for all points on the ice sheet. Errors in these data were removed manually, and the result combined across all five years. The centre points of all lakes that grew larger than two MODIS pixels (0.125 km^2) at any point in this period were recorded. We found we could not extract meaningful information for the purposes of this study from smaller lakes than this using MODIS data. For all 3704 MODIS images we then attempted to grow a region satisfying the spectral criteria described above around each lake centre point, to give a time series of lake areas.

2.4 Error checking

To test for possible errors, the most critical area measurements for each lake were checked against the imagery from which they were obtained, to ensure that the results were not a result of an image artefact or shadowing. We checked the first and last days the lake was visible, and the day when each lake was at its largest in each year. Erroneous values were deleted from the record (2–6 % of data points per year had to be removed on this basis).

2.5 Interpretations of changing lakes area

To examine the behaviour of the lakes, we extracted JPEG thumbnail images from the MODIS data chosen around each lake in the record. These images allowed us to examine visually the changing lake shapes and texture by rapidly flicking through the images using a lightweight image-viewer which allowed folder navigation with the mouse scroll-wheel (the Feh image viewer: https://derf.homelinux.org/projects/feh). This process was time consuming but allowed us to observe lake-drainage processes in great detail.

On examination of the image sequences, it became apparent that the existence of a supraglacial lake on the GrIS can be terminated in three distinct manners. Firstly, lakes can drain rapidly (Fig. 1). Lakes of this type disappear in < 24 h, presumably draining to the bed through hydrofracture (Alley et al., 2005; Das et al., 2008). We reported on the Greenland-wide distribution of these lakes in Selmes et al. (2011).

Secondly, some lakes survive the entire melt season and ultimately freeze (Fig. 2). The freezing of a lake can be inferred through both qualitative and quantitative criteria. For those lakes which appeared to freeze, surrounding lakes also declined in area simultaneously, indicating that the declining lake areas have a common forcing

mechanism, with freezing being the most likely cause. The reflectance of the surrounding ice also increased indicating that surface-melt had ceased, since ice reflectance is lowered as melt increases. Surface temperature from the MOD11A1 MODIS Land Surface Temperature product (LST) of < 0 °C was used as a further proxy of the end of the melt season (Hall et al., 2006), with an assumed error of 1 °C (Wan et al., 2002). This criterion is based upon the expected temperature of melting ice. Lakes shrinking when LST was $< 0 \pm 1$ °C were inferred to be freezing. In addition, for larger lakes during the freezing period the formation of ice on lakes can sometimes be visually identified in the imagery (e.g. Fig. 2).

Thirdly, some lakes underwent areal decline mid melt-season (Fig. 3). In this case, surrounding lakes would continue growing or remain the same size. Using the criteria above we found that this areal decline could occur in periods of consistent melt availability (LST $> 0 \pm 1$ °C). This phenomenon occurred over a range of time-scales, from a few days to several weeks. The timing of these events, often in mid-summer, make freezing unlikely suggesting loss of area by some form of drainage. There is no evidence that drainage through the ice to the bed should occur over a period of several days. Slight water drops that have been observed to occur during the hydrofracture process (Boon and Sharp, 2003; Das et al., 2008) are too small to be detected in these data. The fast increase in ice velocity and uplift associated with sudden lake drainage (Das et al., 2008) shows that total drainage of a lake into an inefficient high water-pressure subglacial environment is possible, as the ice can be displaced to make room for the water. As the drainage speeds of these slower draining lakes were inconsistent with drainage by hydrofracture, we interpret these declines in lake area to be the result of incision of the lake exit-channels leading to supraglacial drainage in the manner described by Liestøl et al. (1980) for Svalbard supraglacial lakes.

We compared the above observations with area/time plots of lakes (e.g. Figs. 1–3) and found that we could categorize most lakes using the relationship between changing lake area and MODIS LST, the criteria used are described below. We used these data to classify lakes into groups of fast-draining, slow-draining, and freezing lakes.

Lakes were first assigned to categories using a computational definition of each class, based upon the rate of areal decline, the stage of the melt season as defined using MODIS LST, and whether adequate cloud-free imagery was available to pinpoint the date of disappearance. A cloud-free observation of the former lake site was required within two days of a lake disappearing for any drainage type to be assigned; those lakes which could not be assigned a category due to cloud were classed as "unknown". Fast-draining lakes were defined using the same method as Selmes et al. (2011), which were required to have disappeared completely within two days, with a cloud-free observation required at the beginning and end of this period. This requirement of rapid reimaging of each lake site eliminated the possibility that if a lake drained slowly during an extended period of cloud it might appear to have drained suddenly.

Freezing lakes appeared in the area data as a gradual decline in lake area, almost always at the end of the melt season. The initial classification of lakes as being of freezing type was made using a combination of lake area and MODIS LST data. An assumption was made that as a melting ice-surface has a surface temperature of 0 °C, the end of the melt season is represented by the last day of the year with MODIS LST of ~ 0 °C. Therefore, freezing lakes were initially defined based upon a gradual decline in surface area with lake disappearance occurring after this decline in MODIS LST. Ambiguous cases were decided upon using the qualitative criteria for freezing described above. Conversely, those lakes with a gradual (three or more days) decline in area where LST remained ~ 0 °C were initially assigned to the class of slow-draining lakes.

Once all lakes had been assigned a class based upon the relationships between time, lake area, and LST, we undertook manual checking using the thumbnail images and qualitative criteria described above. All lakes classified as fast draining or unknown were checked in this way. Some unknown lakes could be recategorized as fast or slow draining where lakes could be observed through thin cloud. All slow draining and freezing lakes that disappeared around the calculated end of the melt season were also checked to ensure the relevant qualitative criteria were met.

3 Results

3.1 Interannual and inter-regional variations in lake type

Between 1931 and 2069 lakes were detected in each year studied. Freezing was the most common reason for a lake disappearing from the ice sheet: ~ 46 % of lakes ended the melt season by freezing. Draining slowly was the next most common mode of termination accounting for ~ 34 % of lakes, with ~ 13 % draining suddenly. No mode of termination could be determined for ~ 7 % of lakes owing to cloud obscuring the drainage period. These values are means for the five year study period. The relative frequencies of termination types were similar for all years (Table 1). The absolute proportions of lakes with each termination type varied interannually however. More lakes froze in 2006 than in others, which is not unexpected as 2006 was a year of particularly low melt. Likewise fewer lakes drained slowly in 2006 than in other years, suggesting some lakes that would have drained slowly froze instead. Slightly more lakes were observed to drain suddenly in 2007 and 2008, however we can present no explanation for why this occurred. 2008 had the fewest drainage events obscured by cloud of any year, which may partly explain this result. Differences in the proportions of drainage types were observed between regions (Table 2, Fig. 4). The differences in the occurrence of fast-draining lakes between regions were significant as reported previously (Selmes et al., 2011), with 61 % of fast lake drainages occurring in the SW region, and only 1 % occurring in the SE. Freezing lakes were more common in northern regions, probably as a result of the shorter melt season in the higher latitudes. Despite these differences the general pattern of freezing lakes being most common, followed by slow draining, with fast draining lakes being least common was observed in all regions of the ice sheet. Note that in Fig. 4 lakes are represented by area whereas Table 1 uses frequency. Comparing the two shows that fast draining lakes tended to be larger than those which drain more slowly, as there are far more slow draining lakes than fast, but the surface area covered is similar in both types.

3.2 Role of elevation

One of the most striking patterns visible in maps of lake type (Fig. 5) is that for several regions the lakes at the highest elevations tended to freeze, this pattern was observed in every year in the period 2005–2009 (Fig. 6). Fast and slow-drainage type lakes tended to occur at lower elevations than freezing ones, with fast-draining lakes in particular conspicuously absent from the highest elevations in all but a handful of cases. In general, fast and slow draining lakes occurred at similar elevations (Fig. 6).

It might seem logical that the highest lakes would be more likely to freeze owing to the shorter melt seasons at higher elevations, this could conceivably result in lakes freezing before drainage can occur. However, freezing lakes had the longest mean duration of any lakes (Fig. 7). These long durations suggest that lakes freezing over did not drain for another reason: drainage was in some way inhibited.

3.3 Interannual variation in lake type

Many lakes disappeared in the same manner in each year of the observation period. However, some lakes exhibited more variation inter-annually. Figure 8a shows for each lake disappearance type, how often that drainage type reoccurred for each lake, expressed as a percentage of all the lakes of that disappearance type. For example, 42 % of all lakes that drained fast did so in one year only, whereas 6 % of lakes that drained fast did so in every year of the dataset. Lakes that froze were most likely to exhibit the same termination behaviour in other years (Fig. 8a). Figure 8b–d show for each lake of a disappearance type, the probability of a different disappearance type occurring in the remaining four years. For example, for each lake that drained suddenly in 1–4 yr, the probability of each of the other drainage types being assigned in the remaining years is calculated and shown in Fig. 8b. Figures 8c–d shows the same calculation for slow draining and freezing lakes. For lakes that drained suddenly in four years out of the five studied, in the remaining year the lake was most likely to be classified as unknown, raising the possibility that several lakes drained suddenly in every year but observations

were missed due to cloud in one year. Slow-draining lakes were most likely to freeze in other years. However it should be noted that in general lakes were 3.5 times more likely to freeze than drain suddenly so this is not unexpected. Conversely lakes that froze were most likely to drain slowly. Freezing lakes were twice as likely to not form in other years than lakes of any other drainage type, with fast and slow-draining lakes having similar probabilities of not forming in other years.

4 Discussion

4.1 Possible causes of lakes freezing

For lakes not to drain, the mechanisms of both surficial and englacial drainage need to be suppressed. In the higher elevation regions where only freezing lakes were found, it is conceivable that these mechanisms could be reduced in efficacy. The convex profile of the ice sheet means that higher elevations have lower surface slopes. These shallower slopes may make surficial drainage less likely to occur. Raymond and Nolan (2000) found that lakes were less likely to drain through the downwasting of the exit channel (in that case, an ice-dammed lake) where surface slopes were gentler. Until field studies reveal what causes a supraglacial lake to drain suddenly it is not possible to evaluate why this cause is not operating at higher elevations. Lack of sudden lake drainage must mean either the absence of fractures to propagate, or that these fractures are prevented from propagating to the bed. The absence of fractures would indicate lower strain rates at these lake sites. It is also possible that the thicker ice at higher elevations makes hydrofracture to the bed of the ice sheet more difficult. Whilst Krawczynski et al. (2009) demonstrated numerically that drainage through 1000 m of ice by a large lake is not problematic, small drops in water level associated with hydrofracture observed over much thinner ice by Boon and Sharp (2003) suggest that in reality it is not always so simple. However, we did not find that there was a firm elevation threshold beyond which lakes would no longer drain to the bed. Another possible control is that the highest lakes tend to form on firn, it may be possible that this firn layer provides a buffer between the water body and the underlying fractures preventing hydrofracture from initiating.

This possible elevation restriction must be understood before the future role of surface melt forcing on ice sheet velocity can be inferred. It has been stated (e.g. Sundal et al., 2009) that as the warming climate leads to lakes forming at higher elevations, more lake drainage to the bed should be expected, and therefore more connections between the surface and basal hydrologies would be established. Our data cannot show whether this is to be expected in the long term or not. However, our results do show that the relationship between the maximum elevation that lakes form to and the elevation at which lakes drain to the bed is not straightforward. In fact, the lakes at the highest elevations tend to freeze. We have been unable to establish the reasons for this phenomenon. If thicker ice inhibits lake drainage to the bed, this will provide an upper limit on surface-melt forcing of ice sheet velocity in a warmer climate. However, if the lack of lakes draining to the bed at higher elevations is a result of another control such as a firn layer, we can expect hydrological connections between the surface and ice sheet bed at every increasing elevations as the climate warms, although the relationship between the elevation at which this occurs and melt availability will not necessarily be a linear one.

4.2 Slow and fast draining lakes: inference for drainage initiation

We found that lakes that drained suddenly in one year would often drain slowly in the next, suggesting that whatever mechanism controls whether or not a lake can drain suddenly must be ephemeral. A possible control may be the availability of suitable fractures through which drainage can occur.

During the classification process described above we observed groups of lakes sometimes draining suddenly on the same day, with several lakes, often arranged linearly, disappearing between observations. Examples of this phenomenon are shown in Figs. 1 and 9. The most obvious explanation of these events is that the sudden

drainage of one lake causes the widening and/or propagation of a fracture through the sites of other local lakes. We attempted to quantify these events, however with the data available it is unclear how close two drainage events would have to be spatially to be considered linked. For this analysis we chose to look for fast-drainage events within 25 MODIS pixels of each other, or 6.25 km. To be allocated to a cluster of fast-draining lakes, a lake had to be within 6.25 km of a lake within that cluster, therefore each cluster could cover a region with a greater diameter than 6.25 km. This limit of ~ 6 km was set to quantify these events over the spatial scale that we observed them occurring. Das et al. (2008) observed a 3.2 km long fracture running through the former site of a lake that drained suddenly, and a similar observation was made by Doyle et al. (2013). The choice of area makes a significant difference to the results of this analysis. Using this spatial criteria, in the years 2005–2009, 13, 8, 11, 11, and 15 groups of potentially linked fast-draining lakes were identified, with 2–4 lakes per group. These groups were found in all regions of the ice sheet except the SE. However doubling the search area and allowing a 48 h window instead changed this result to 18–37 groups of 2–8 lakes.

The fact that lakes can drain in clusters in this manner suggests that even if this simultaneous drainage is not the result of one interconnecting fracture enlarged by one drainage event, it is indicative of some trigger with localized effects whether an enlarging fracture or a sudden change in the local stress regime. To date no research has shown why a fast draining lake should drain on a particular day. While it might seem logical that, as fast draining lakes typically have larger mean surface area than slow draining lakes, a lake would need to reach a critical volume before drainage can occur. However, in several cases lakes were observed to grow larger in years where they did not drain suddenly. Figure 10 shows a lake which drained in four years out of five, freezing over at the end of the fifth melt season. The lake reached its second largest size in 2009: the year it did not drain suddenly. In 2005 the lake drained with around one fifth of the area at which it drained in 2008 and froze in 2009. In the years that it drained, this lake drained as part of a cluster of fast draining lakes. In 2009 the other lakes in this cluster drained suddenly but this lake did not, suggesting that the fractures linking the lakes did not reach the lake in question. These findings suggest that lake area and hence almost certainly lake depth is not necessarily a good indicator for drainage behaviour, and that some other mechanism triggers lake drainage in at least some cases.

4.3 Importance of different lake types for ice dynamics

It is important to be able to distinguish between fast and slow lake-drainage events when considering the relative effects on ice sheet dynamics. Both drainage types could allow melt water from the surface to reach the bed of the ice sheet. In fast draining lakes this would occur rapidly at high pressure, through new, vertical conduits formed through hydrofracture. Lakes draining supraglacially could do so across the surface initially, with the water potentially then entering a pre-existing moulin; any water reaching the bed in this manner would do so more gradually and at lower pressures than in the fast draining case. Drainage speed is important for ice sheet dynamics for two reasons. Firstly, water initially draining supraglacially is less likely to generate new englacial conduits for drainage to the bed than with catastrophic lake drainage, as water is delivered to existing fractures more slowly. Secondly, water entering an efficient subglacial network slowly can be discharged without little effect on ice dynamics (Schoof, 2010). Water entering an efficient drainage network in a sudden pulse as in a lake drainage event can overwhelm the system, reducing effective pressure and temporarily increase ice velocity.

It should be noted that freezing lakes probably do play a role in the wider supraglacial melt system. It is reasonable to assume that some lakes which freeze may also be draining continuously over the ice sheet surface through an exit channel, however this drainage is stable and only balances the inputs into these lakes. The only difference between these lakes and those described here as slow-draining, is that in the latter lakes the drainage through the exit channel becomes so rapid that the exit channel incises rapidly enough that the lake drains totally.

To distinguish between these lake types frequent observations are required. It is not possible to distinguish between a lake which has drained suddenly and one which has drained more slowly from satellite imagery of the drained lake site alone. This has important implications for the remote sensing of supraglacial lakes. It is not sufficient to note the absence of a lake from one image to the next and assume drainage to the bed has occurred unless these image are 48 h or less apart. This is problematic for the use of higher spatial resolution sensors such as Landsat and ASTER, as the repeat time of these sensors are not sufficient to determine which drainage type has occurred.

While it is not possible to distinguish between fast and slow-draining lakes based on infrequent remote-sensing observations, the timing of observations can often give a good idea of the fate of a lake disappearing from the ice sheet. A lake that disappears between two images at the very end of the melt season is far more likely to have frozen over than drained. As an example, Joughin et al. (1996) is often cited as an example of supraglacial lake drainage influencing the velocity of outlet glaciers, which has been reported elsewhere to be less significantly affected by melt forcing than land-terminating ice (Joughin et al., 2008). Two lakes were observed to disappear from the surface of Ryder Glacier between the imagery used to established that the glacier had experienced a small surge. However, the lakes referred to in that study disappeared between September and October 1995. Our results show that for the years included in this study it is most likely that those lakes froze over as a result of the end of the melt season. The study presented here includes 2008, a record melt year in the north of Greenland (Tedesco, 2008) where Ryder Glacier is located. Even in the record melt year of 2008, all lakes in the Ryder Glacier area were freezing by September, and were all frozen by October, making it most likely that those lakes observed by Joughin et al. (1996) froze, meaning that they are unlikely to have played a role in the surge of Ryder Glacier.

5 Conclusions

Frequent observations of the supraglacial lakes on the Greenland Ice Sheet allow us to make inferences of the drainage behaviour of these lakes. We conclude that any lake on the ice sheet has one of three probable fates. Sudden drainage to the bed of the ice sheet which has been well studied previously on account of its possible role in ice sheet dynamics. However, this is the least common reason for a lake to disappear from the ice sheet. Around half of all lakes survived the summer without net drainage, and froze at the end of the melt season. Approximately a third of all lakes drained more slowly over several days to weeks, probably through the incision of the lake exit channels. The latter two processes have not been reported for lakes in Greenland, and we are inferring these behaviours from our observations, and reports from Svalbard (Liestøl et al., 1980). These observations, particularly the recognition of these two additional termination types lead us to urge caution for remote sensing studies of supraglacial lakes, as inadequate temporal sampling will easily lead to the overestimation of sudden lake drainage.

Lakes were found to be more likely to freeze at higher elevations, however freezing lakes had the longest durations indicating that mechanisms of drainage was inhibited. While fast draining lakes were generally larger than slow draining ones, lakes were observed to grow larger in years they did not drain suddenly, indicating that lake area and therefore almost certainly water depth is not always a good indicator for whether a lake will drain suddenly or not, and that another trigger for fast drainage is needed. The existence of apparently linked drainage events when several fast drainages occur in adjacent lakes supports this hypothesis, indicating either a linking fracture or a change in the local stress field. All these findings combined indicate an unknown first-order control on fast lake-drainage and we hypothesise this must be related to either the pre-existence or generation of fractures prior to the hydro-fracturing process.

Published fieldwork on Greenland lakes has to date focussed on those lakes which drain to the ice sheet bed. We argue that more research is needed not just into the

characteristics of lakes which drain to the bed, but also into those that do not. Establishing why so many lakes do not drain will allow better predictions of the role of surface meltwater in the dynamics of the future Greenland Ice Sheet.

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Table 1. The fate of lakes on the Greenland Ice Sheet for each of the five years studied, expressed as a percentage of all lakes observed. The total number of lakes in our dataset in each year is also shown.

	2005	2006	2007	2008	2009
Fast	11.9	11.3	14.3	14.7	12.0
Slow	35.1	24.5	37.6	38.6	34.2
Freeze	46.5	58.0	38.1	44.9	48.1
Unknown	6.4	6.2	7.4	4.6	5.7
Total frequency	2067	1996	2069	2127	1931

Table 2. The fate of lakes in the different sectors of the GrIS, expressed as percentages of all lakes in that sector and averaged across the five years studied. See Fig. 4 for the region boundaries.

	Fast	Slow	Freezing	Unknown
SW	14	37	40	8.1
NW	7.4	31	57	5.0
N	14	22	55	8.8
NE	17	27	52	3.9
E	9.7	42	45	3.4
SE	7.7	48	40	4.9
GrIS	13	34	46	6.7

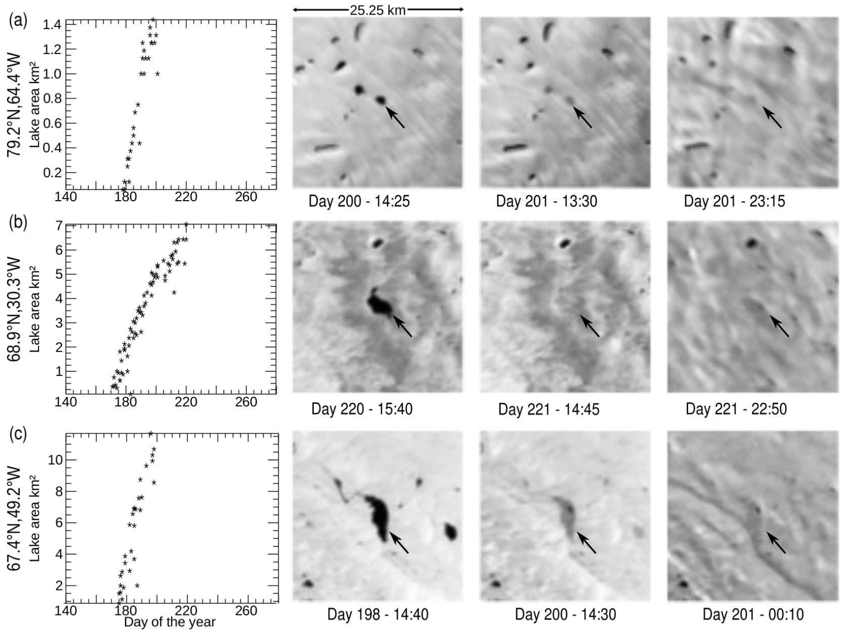

Fig. 1. Examples of lakes that drain suddenly. All images are at the same scale and show MODIS band 1 250 m images before and after drainage events. Note simultaneous drainage in **(a)** and **(c)**. The area/time plots correspond to the lakes indicated by arrows.

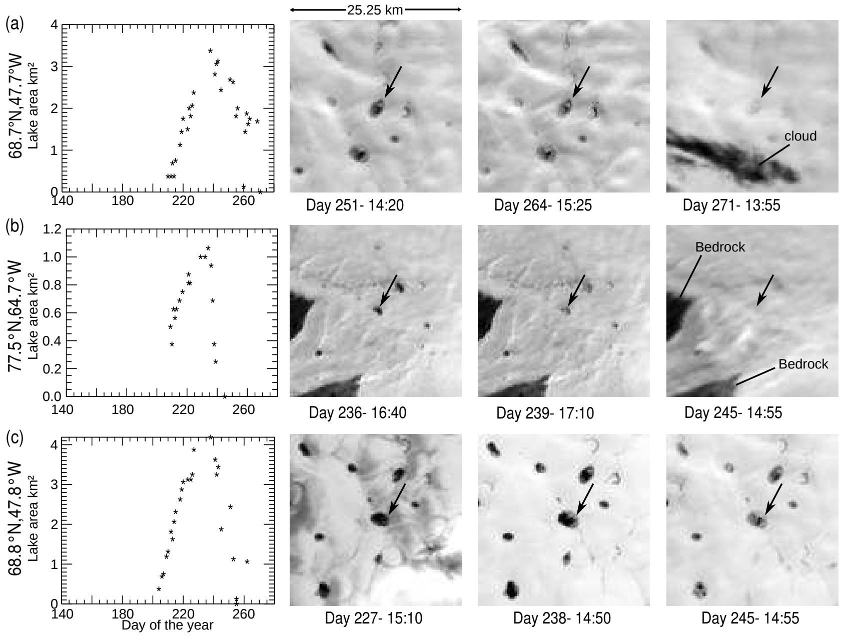

Fig. 2. Examples of lakes that were observed freezing over at the end of the melt season. Note that in each case all of the lakes in the image have declining area at the same time, this is taken as strong evidence of freezing as opposed to supraglacial drainage. Also note in examples **(a)** and **(c)** that ice can be seen encroaching on the lake surface. Example **(c)** also shows a general increase in the albedo of the surrounding ice which is indicative of the end of the melt season.

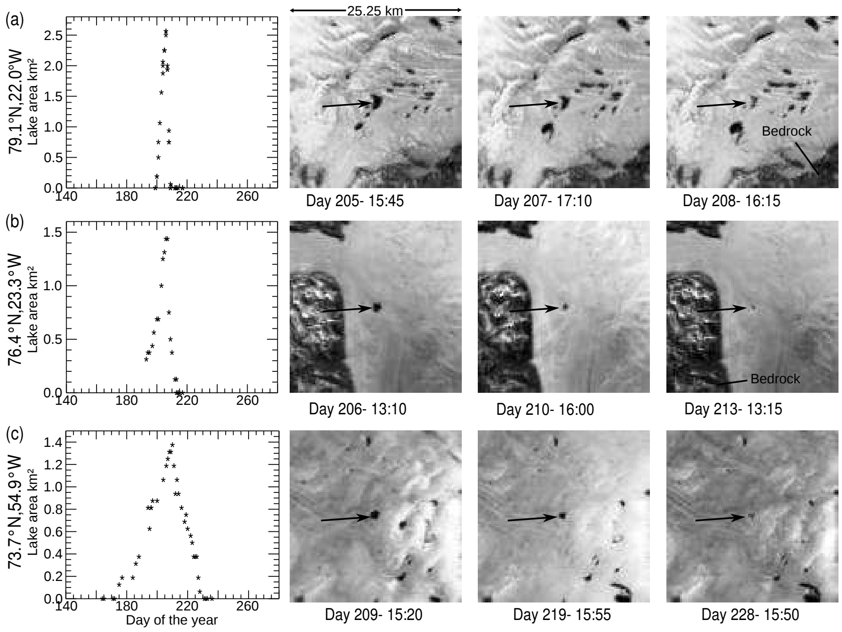

Fig. 3. Examples of lakes that were observed draining slowly. Note that in examples **(a)** and **(c)** other lakes in the surrounding area do not lose area, providing strong evidence that the lake in the centre of the image is draining rather than freezing. The albedo of the surrounding ice in each example remains relatively low indicating a melting surface.

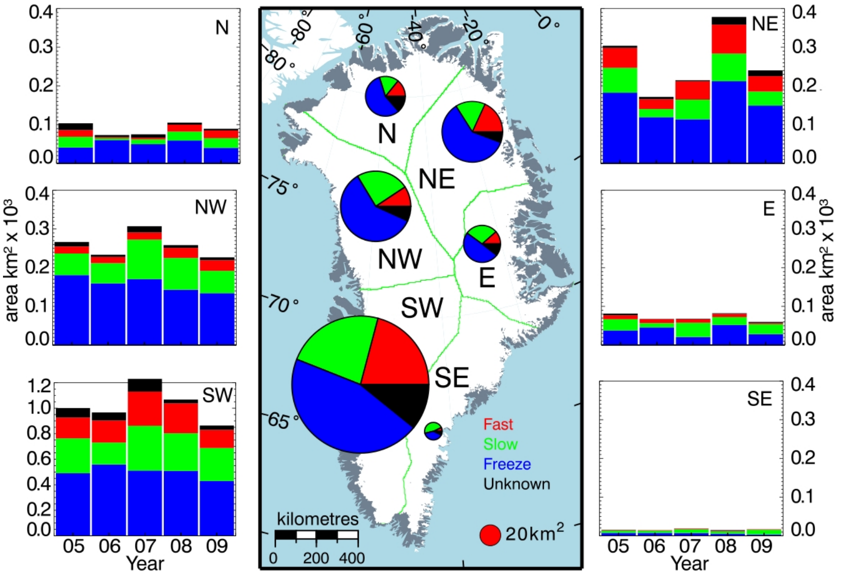

Fig. 4. The distribution of lake drainage types on the GrIS. Lakes are represented by maximum surface area in each year. The central figure shows the mean area of lake types over the period 2005–2009. The bar charts show the area and proportions of lake drainage type per year. Fast-draining lakes (red), slow draining lakes (green), and freezing lakes (blue) are shown. Lakes of unknown drainage type are also shown (black). Note that a different vertical scale is used for the SW bar chart for clarity.

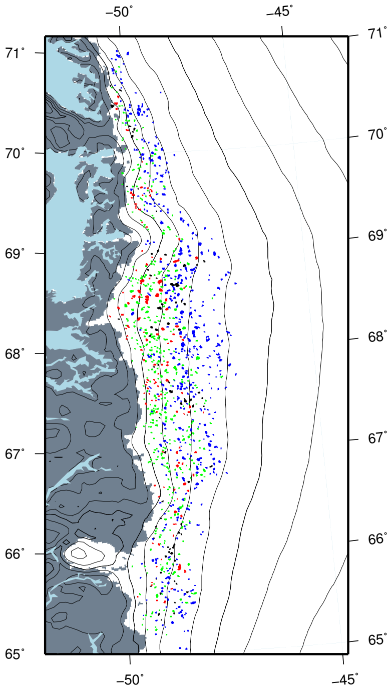

Fig. 5. Distribution of different drainage types in SW Greenland during 2005, showing fast-draining lakes (red), slow-draining lakes (green), freezing lakes (blue), and lakes of unknown drainage type (black). Freezing lakes tended to occur at higher elevations than those lakes which drained either fast or slowly.

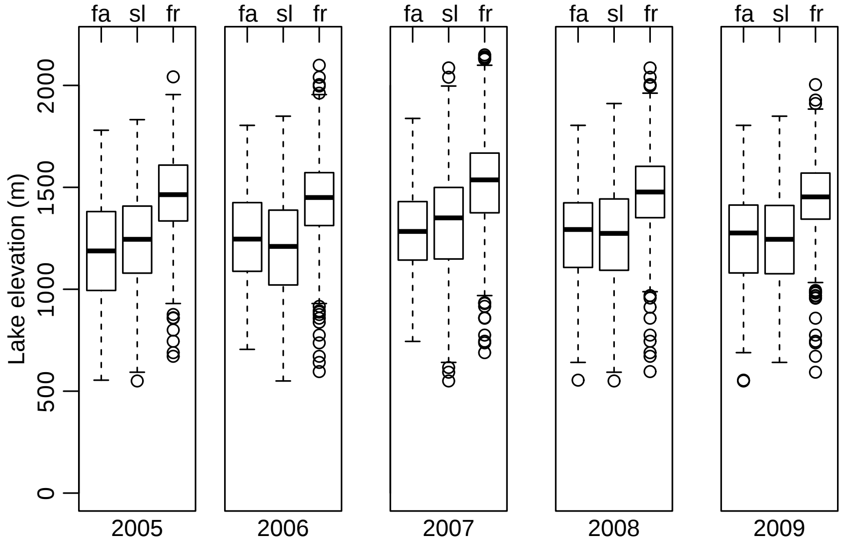

Fig. 6. Box and whisker plots to show the elevations of lakes of different types through the period 2005–2009, for the SW sector of the ice sheet (south of 71° N). Fast draining (fa), slow draining (sl) and freezing (fr) lakes are shown. Freezing lakes consistently formed at higher elevations than those which drained. However, there was overlap between these groups. The box indicates the interquartile range, the central mark the median, and the whiskers the range without outliers. Outliers are defined as as values exceeding 1.5 times the interquartile range above/below the upper/lower quartile, and are shown as circles.

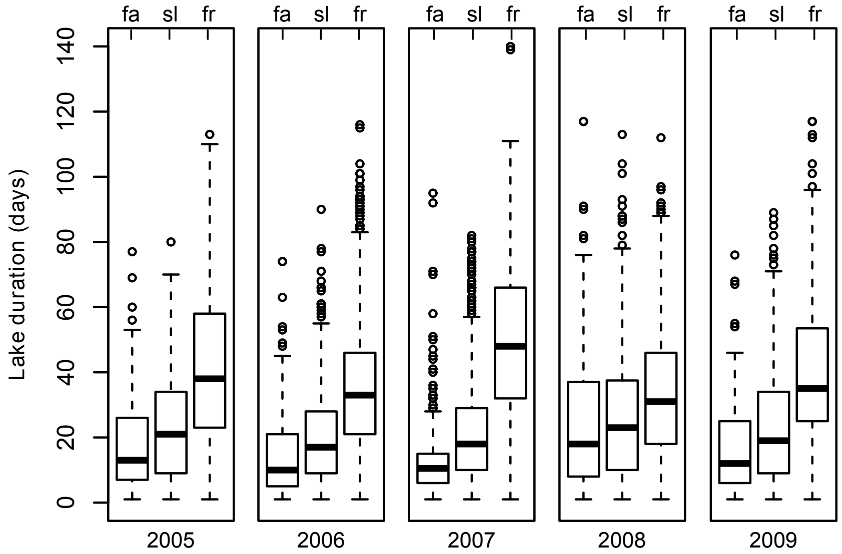

Fig. 7. Box and whisker plots to compare the duration that lakes that drained fast (fa), slowly (sl), and froze (fr), existed on the ice sheet. Freezing lakes consistently had the longest duration of existence, and fast draining lakes the shortest.

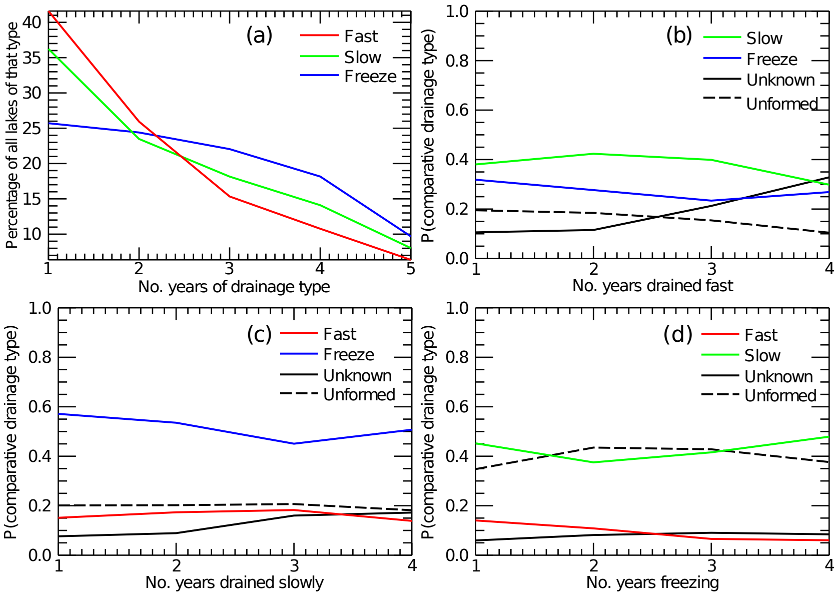

Fig. 8. The persistence of drainage types. **(a)** How often each drainage type reoccurred for the same lake in different years, as a percentage of all lakes with that drainage type at least once. **(b–d)** For lakes that drained fast **(b)**, slowly **(c)**, or froze **(d)**, the probability (P) that a lake with that drainage type in 1–4 yr will have had each of the other drainage types in the remaining years is plotted.

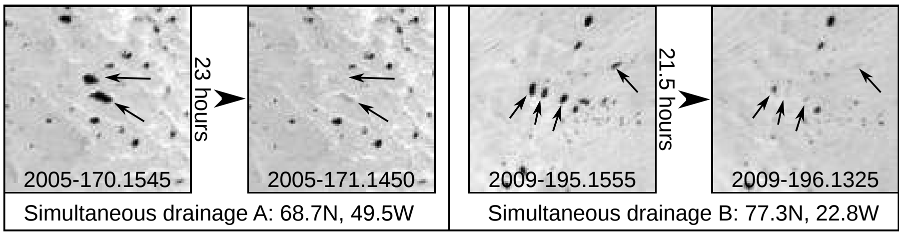

Fig. 9. Examples of apparently linked fast-drainage events in MODIS band 1 imagery. In both examples two or more lakes in a region drained fully or partially in the same day. Example **(A)** is in SW Greenland, and example **(B)** in NE Greenland. Lakes which drained are identified in before and after images with arrows.

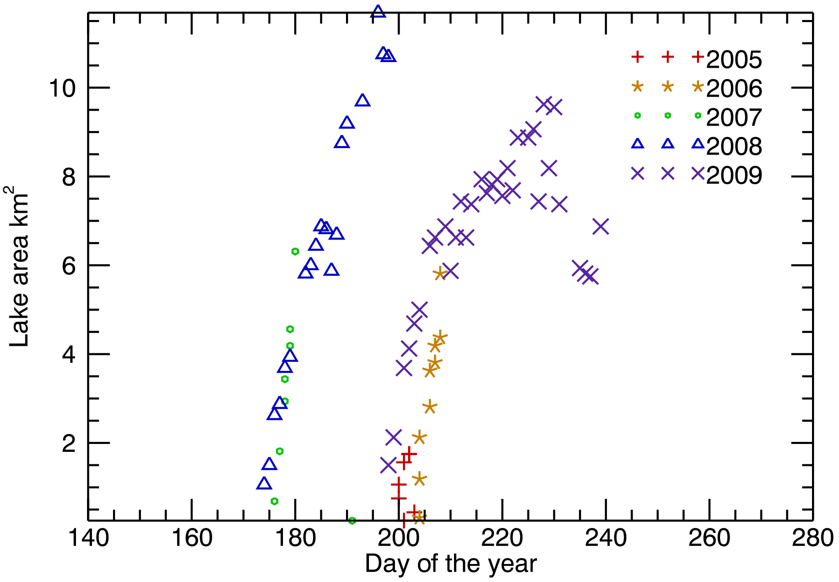

Fig. 10. Lake area plotted against time for the lake at 65.85° N, 48.75° W for the five years studied. In four of the five years (2005–2008) the lake drained suddenly. In 2009 the lake froze over instead, despite the lake reaching its second largest extent of the study period, growing around the same date as in two other years, and surviving on the ice for the longest duration of any year.