Determining the date of ice-melt for low Arctic lakes along Søndre Strømfjord, southern West Greenland

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The length of ice cover has considerable influence on the functioning of lake ecosystems, particularly so in continental and high-latitude regions where lakes freeze annually. Long-term trends in the length of ice cover and the date of ice break-up can be related to regional weather patterns, such as the North Atlantic Oscillation. It is this relationship to weather patterns that has generated considerable interest in the use of long-term ice-records as climate proxies. Although it is reasonable to assume a relationship between the length of the ice-free period and lake productivity, it is unclear if this relationship influences the sedimentary record. Whether these ice-climate interactions can be identified in the sediment record is important for distinguishing long-term palaeoclimatic trends from variations in the sediment record (Anderson *et al.* 2000).

In the high Arctic, ice cover is often nearly permanent from year to year and the extent of moating is important for biological processes. An ice remnant on a lake during one summer can increase water temperatures the following spring (Doran *et al.* 1996). This increased spring temperature is caused by the remnant ice trapping heat in the lake together with reduced convective cooling. As a consequence, this process reduces the likelihood of two consecutive years with residual ice. In the low Arctic, where low-altitude lakes are normally completely ice-free every summer, it is the timing of the spring ice-melt period and the total length of the ice-free period that can be important for biogeochemical processes. For example, the break-up of the ice is associated with emergence of chironomids and their mating (Brodersen *et al.* 2001, this volume) while prolonged ice-cover and anoxia will influence internal biogeochemical cycling of nutrients and alkalinity generation. The length of the ice cover period, coupled with the rapid development of thermal stratification is one

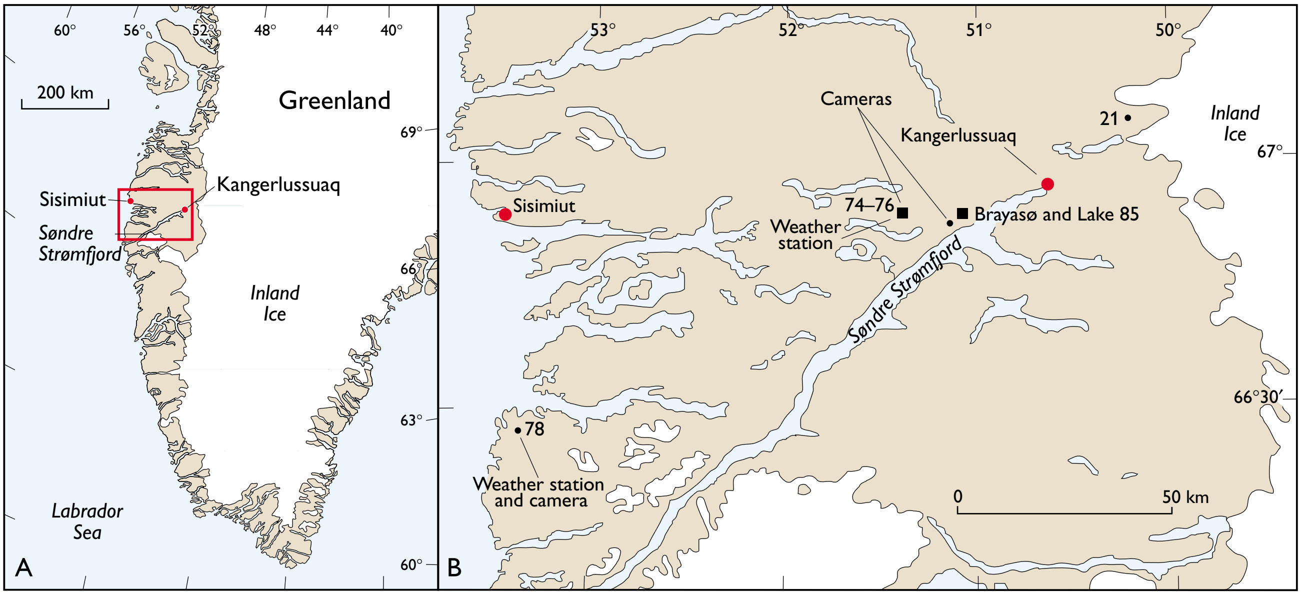


Fig. 1. **A**: The study area in southern West Greenland. **B**: The study area with location of cameras, automatic weather stations and lakes with thermistor chains. ■ = group of lakes; • = individual lake. Modified from Brodersen & Anderson (2000).

of the reasons why so many lakes in southern West Greenland have laminated sediments (Anderson *et al.* 2000). At the regional scale the main factors governing the timing of ice-melt and the length of the ice-free period are radiation input and air temperature, altitude, lake area and volume.

There is considerable geographic and inter-annual variability in the length of ice-free period in lakes (freeze and break-up date). An analysis of all available data for time series over 100 years in length from lakes throughout the world has revealed a trend for freeze dates to have occurred 5.8 days later per 100 years and break-up date 6.5 days earlier per 100 years (Magnuson *et al.* 2000). Determining the date of ice break-up has traditionally been based on continuous field observations, some of which cover hundreds of years (e.g. Lake Suwa, Japan), recorded for cultural or religious as well as scientific reasons (Magnuson *et al.* 2000). However, there are very few data on ice-melt dates for remote lakes, such as the many thousands in the ice-free area of southern West Greenland. In this project, we follow the process of ice-melt to the date of final disappearance of ice (ice-out).

Recent sporadic field observations along Søndre Strømfjord by the authors indicate that ice-melt occurs earlier in those lakes closest to the head of the fjord, largely reflecting the climate gradient in this area (Hasholt & Søgaard 1976). At the coast, where the summers are cooler and fog banks reduce radiation input, lakes can still be completely ice covered with minimal moating, when ice-melt on the lakes close to the airport at Kangerlussuaq (Fig. 1) is nearly complete. Previous field work in this area (Anderson *et al.* 1999) also indicates substantial variation from year to year. For example, in 1998 lakes around the head of the fjord were largely ice-free by mid-June. The following year, 1999, when mean April–May temperatures were ~ 2°C lower than in 1998, ice-melt was still not complete by 1 July.

In this paper, and on Fig. 1, we follow the convention of referring to the fjord as Søndre Strømfjord and the airport at the head of the fjord as Kangerlussuaq; the fjord is also known by its Greenlandic name Kangerlussuaq.

Use of satellite imagery is useful and can cover large numbers of lakes, but its application can be limited by cloud cover, resolution – not all the smaller lakes in a given area are easily visible (Wynne *et al.* 1996) – and temporal coverage. As much palaeoclimate work is based on sediment records from small lake basins, this lack of information for smaller lakes can be problematical. It was decided, therefore, to attempt an alternative approach using automatic cameras and lake-water temperature dataloggers.

Field activities in 2000

The aim of field work in 2000 was to establish local monitoring systems that could be used to record the date of ice-out at locations along the climate gradient from the Inland Ice margin to the coast south of Sisimiut (Fig. 1). It was hoped that by assembling information

Fig. 2. Downloading data from the automatic weather station near Lake 78 on 29 August 2000. For location, see Fig. 1B.

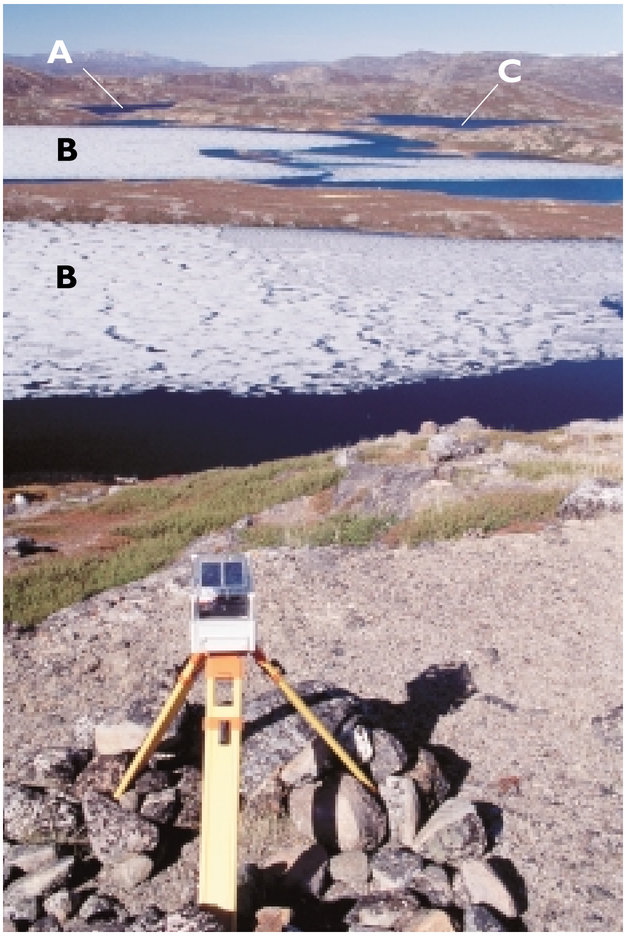


Fig. 3. Remote-controlled camera overlooking Lakes 74 (**A**), 75 (**B**) and 76 (**C**). The height of the camera and tripod is about 1.4 m.

about the date of ice-out and local meteorological conditions it would be possible to generate a simple empirical model that could be used to predict future ice-out dates.

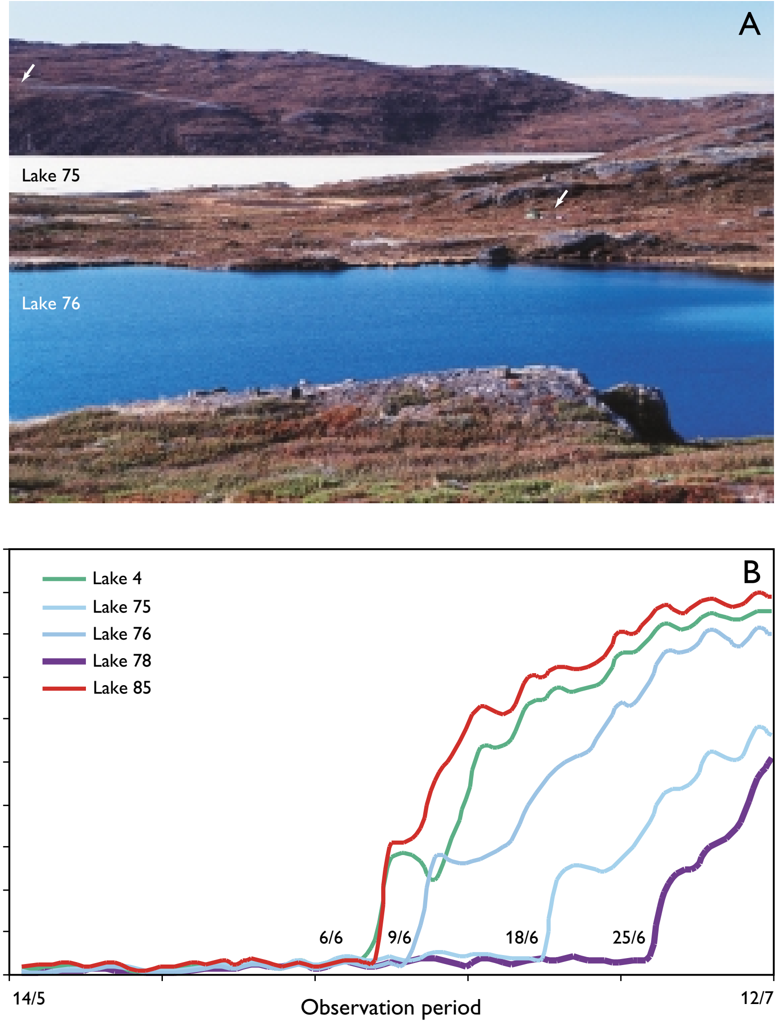
The study sites are spread along the climatic gradient (continental to more maritime) from the Inland Ice margin to the coast south of Sisimiut. Two lakes close to the head of the Søndre Strømfjord were sampled (Lake 4 = Brayasø and Lake 85) together with Lakes 75 and 76, approximately half way along the fjord. The most easterly site was Lake 21, and the most westerly, Lake 78 (Fig. 1B). The lakes cover an altitude range from 45 m to 470 m and vary in area from < 10 ha to ~ 140 ha. Maximum depths range from 14 to 50 m.

The main field work in 2000 took place between 23 April and 6 May and consisted of the deployment of thermistor chains (Brodersen & Anderson 2000), automatic weather stations and cameras. At five lakes (Lakes 4 = Brayasø, 22, 75, 76, 78; Fig. 1B) chains of thermistors were deployed (10–12 per lake depending on the maximum depth). Thermistors were set to record water temperature at hourly intervals. They were attached to steel wires to reduce the possibility of the ice cutting them and dropped through a hole cut in the ice. The automatic weather station (AWS) between Lakes 75 and 76 was upgraded (to measure solar radiation), and a similar system was erected adjacent to Lake 78 near the coast (Fig. 2). At three sites (Fig. 1B), an automatic digital camera was set up overlooking an individual lake (i.e. Lake 78) or groups of lakes (i.e. close to Brayasø and Lake 85, and overlooking Lakes 74–76; Fig. 3). Standard digital cameras were placed in a waterproof housing, and the cameras were set to take a picture at noon every day using an attached electronic timer (Fig. 3). All systems were in operation by 6 May. With this monitoring system, it was hoped that it would be possible to correlate exactly the date of ice-out (derived from photographs) with changing water temperature and local meteorological data.

A return visit to the study sites was made in August and AWS data and the camera images were downloaded in the field (Fig. 2). At the same time the thermistor chains were changed, and then returned to the lakes. Although the intention of the project was to record data over two ice-melt periods, this late summer visit meant that if the lake-water temperature thermistor chains were lost during the winter of 2000–2001, data for the first ice-melt period was secure. Unfortunately, it was found that one camera had failed to record any images and another took only random images.

The photographic sequence at Lakes 75 and 76 showed that the final break-up of the ice is very rapid. The water temperature record derived from the thermistors indicates that there is a rapid increase in temperature (*c.* 5°C over a few hours) associated with the final break-up of the ice (Fig. 4B). This temperature rise is, presumably, due to the mixing of the water column and transfer of 'warmer' water (*c.* 4–5°C) from depth. Over the ~ 10 days prior to the final break-up of the ice there is a gradual warming of the surface water under the ice due to either radiative heating as the ice thins (and day length increases) and/or the transfer of warmer water from the littoral moats. Using the rapid rise in temperature as an indication of ice break-up we were able to estimate the dates of ice-out at the other lakes. The earliest lake to be ice-free in 2000 was Brayasø (Lake 4) on 6 June. This lake was followed closely by Lake 85 (which drains into Brayasø) on 7 June and Lake 76 on 9 June. Lake 75, although immediately adjacent to Lake 76 is much larger (144 ha versus 8.6 ha)

Fig. 4. **A**: Overlooking Lakes 75 (still ice-covered) and 76 showing the effect of lake area and depth on ice break-up. Camera on hill top (**arrow**) and camp site (**arrow**) between lakes with an inter-distance of 1.56 km (15 June 2000). For location, see Fig. 1B. **B**: Plots of surface-water temperature for all lakes showing the very clear rise in temperature associated with the final break-up of the ice and mixing of the water column. Lake 4 = Brayasø.



and as a result ice-out was delayed by nearly 10 days (18 June 2000; Fig. 4A). Finally, as with our previous field experience, the coastal site (Lake 78) was the last to be ice-free on 25 June 2000. We were not able to retrieve the thermistor string from Lake 21 during our late August field trip and so the ice-out date there is unknown. The lake lies close to the Inland Ice margin and it remains to be seen whether there is a pronounced effect associated with the strong meteorological gradient in this area (Hasholt & Søgaard 1976).

One of us (K.P.B.; see Brodersen *et al.* 2001, this volume) was present in the field at the time of the break-up of the ice on Lake 76 and field observations confirm the rapidity and timing of the ice break-up at this lake (Fig. 4A). Although only one lake, these field observations lend support to the reliability of the camera results. The use of remote-controlled cameras offers a relatively cheap means of tracking environmental change visually on a seasonal basis.

Conclusion

Understanding ice phenology in West Greenland is vital to our understanding of long-term lake-climate interactions and interpretation of the sediment record. Sediment coring at lakes around Søndre Strømfjord indicates considerable variability in both lake biota and physical properties. Some of the long-term trends will be related to soil and landscape development as well as climatic change during the Holocene. However, much of the finer, short-term variability is presumably related to factors such as length of ice cover and processes controlling transfer of nutrients from catchment to lake. Finally, modelling of earlier climate-lake interactions using lake energy balance models requires a fuller understanding of present-day relationships between ice cover period, water temperature and regional meteorological conditions. The different automatic monitoring equipment used in the present study (digital cameras, temperature thermistors and AWS) represents a reasonably cost effective way of acquiring important site-specific field data on the process of ice-melt in remote lakes.

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