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Published in:
PAGES News

DOI:
10.22498/pages.21.1.12

Publication date:
2013

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Andresen, C. S., Straneo, F., Ribergaard, M., Bjørk, A. A., Kuijpers, A., & Kjær, K. H. (2013). Using marine sediment archives to reconstruct past outlet glacier variability. *PAGES News*, *21*(1), 12-13.
https://doi.org/10.22498/pages.21.1.12

Using marine sediment archives to reconstruct past outlet glacier variability

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Ice-rafted debris in fjord sediment cores provides information about outlet glacier activity beyond the instrumental time period. It tells us that the Helheim Glacier, Greenland's third most productive glacier, responds rapidly to short-term (3 to 10 years) climate changes.

Sea-level rise is one of the major socio-economic concerns associated with global warming, since millions of people live within coastal floodplains that are situated less than 1 m above present sea-level. The latest IPCC report suggested a sea-level rise of 0.18 to 0.59 m within the next 100 years (IPCC 2007), but emphasized that the contribution from outlet glaciers is the largest source of uncertainty. Since then, several studies (see SWIPA 2011 for references) have suggested that the contribution from outlet glaciers could be +1 m or more.

The concern about unexpected glacier dynamical behavior was highlighted when the three largest outlet glaciers in Greenland were observed to suddenly increase their discharge at the onset of this century. Specifically, Jakobshavn Glacier in west Greenland, Kangerdlugssuaq Glacier and Helheim Glacier, both in Southeast Greenland, accelerated, thinned and retreated between 2000 and 2005 (Fig. 1A, Rignot & Kanagaratnam 2006; Van den Broeke et al. 2009). In the case of Jakobshavn Glacier, researchers proposed that the acceleration was triggered by a warming of the subsurface ocean currents off West Greenland (Holland et al. 2008) consistent with the mid-1990s warming of the North Atlantic subpolar gyre, which feeds the waters off West Greenland via the Irminger Current (Buch et al. 2004; Holliday et al. 2008; Stein 2005). The ocean warming, in turn, was attributed to a shift from a positive to a negative North Atlantic Oscillation (NAO; Hurrell 2001) phase and additional changes in the low-pressure systems causing a westerly movement of the subpolar frontal system (Flatau et al. 2003; Hatun et al. 2005). The westward spreading of the warm subpolar waters contributed to a warming of the West Greenland continental shelf and an increase in the rate of submarine melting of the glacier front, thereby increasing iceberg calving rates and mass loss (Rignot et al. 2010).

This hypothesis of glacier melting caused partly by warm subsurface water penetration into the glacial fjords has also been suggested to explain the acceleration of outlet glaciers in Southeast Greenland (Christoffersen et al. 2011; Murray et al. 2010; Nick et al. 2009; Straneo et al. 2010). For example, Sermilik Fjord, where the Helheim Glacier terminates, is characterized by a thick layer of ~4°C warm Atlantic water of Irminger Current origin, underlying cold Polar water of glacial and Arctic origin (Fig. 1A; Straneo et al. 2010). However, as fjord water properties have only been monitored here since 2008, it has proven difficult to confirm such a causal relationship between oceanographic and glacier variability. Furthermore, relatively rapid mass changes of the Greenland ice sheet have only been estimated from satellite data since the early 1990s. Thus, a comprehensive understanding of the inter-annual to decadal variability of the ice sheet on longer timescales is lacking. Without longer records it is difficult to evaluate if the recent mass loss is an outstanding event or is part of a recurring phenomenon acting on inter-annual, decadal or centennial timescales, or a combination of both.

Reconstruction of Helheim Glacier calving variability

The link between climatic changes and outlet glacier variability was recently investigated in a study of past changes of Helheim Glacier going back 120 years, analyzing three marine sediment cores retrieved in Sermilik Fjord (Fig. 1B; Andresen et al. 2012). We reconstructed the calving variability based on the assumption that changes in the deposition of sand (ice-rafted debris) directly relate to changes in iceberg rafting from calving activity. The resulting record documents a series of calving events lasting 3 to 10 years (Fig. 2A). The use of the sand deposition as a recorder of the calving history of Helheim Glacier is supported by the agreement between the reconstructed calving changes and the changes in frontal position of the Helheim Glacier since 1933 as observed from satellite data and historical aerial photographs (Fig. 1C, Fig. 2A-B).

Exploring a link with climate

Increased air and ocean temperatures (both surface Polar water and subsurface Atlantic water) may increase glacier calving through

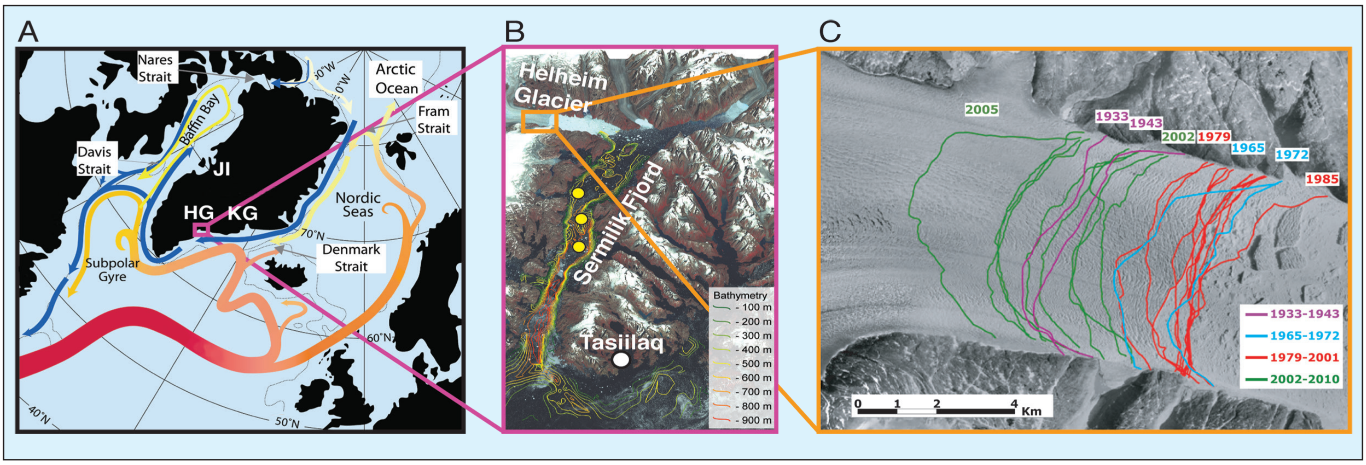

*Figure 1: **A)** Main currents in the North Atlantic Ocean (Straneo et al. 2012) and location of Helheim Glacier (HG), Kangerdlugssuaq Glacier (KG) and Jakobshavn Isbrae (JI), **(B)** Helheim Glacier and Sermilik Fjord with position of the three cores (yellow dots) taken from water depths 500-600 m (bathymetry from Schjøth et al. 2012 and figure from Andresen et al. 2012) and **(C)** frontal variation in Helheim Glacier margin position from 1933 to 2010 grouped into time frames characterized by similar frontal behavior (from Andresen et al. 2012).*

a number of processes involving destabilization of the glacier margin (Motyka et al. 2011). Examples of such processes are ocean water undercutting and melting the submerged glacier margin, surface glacial melt water penetrating down the ice sheet, forming crevasses and promoting iceberg formation, or destabilization of the dense ice mélange (mixture) of icebergs and sea ice in front of the glacier margin (Amundson et al. 2010; Vieli and Nick 2011). To investigate potential links between climate variability and Helheim Glacier instability we compared the calving history with records of nearby oceanic and atmospheric variability (Fig. 2). Air temperature variability was taken from the observed summer temperatures at Tasiilaq (Fig. 2C). No long-term ocean measurements are available from Sermilik Fjord or the nearby shelf. Therfore, we used several indirect indicators for subsurface Atlantic water and surface Polar water: (1) Direct measurements of sea surface temperature (SST) from south of Iceland, where Atlantic water extends to the surface while flowing towards southeast Greenland and sliding underneath the East Greenland Current, were used as a measure of Atlantic water variability (Fig. 2D). (2) Changes in the Storis Index related to the amount of sea ice in the East Greenland Current, were used as a measure of Polar water variability (Fig. 2E). (3) Atlantic water and Polar water variability were combined into a so-called Shelf Index (Fig. 2F) assuming that the variability of waters on the shelf mostly reflects changes in the relative volume of these water masses: a positive Shelf Index indicates a thicker and warmer Atlantic water (at the expense of Polar water) and vice versa.

Finally, we compared the calving record with the wintertime NAO Index, which represents the dominant mode of atmospheric climatic variability in the North Atlantic region (Fig. 2G).

Rapid glacier response to climatic changes

We find that the calving variations are linked with synchronous changes in the source of Atlantic water and with local summer air temperature at multi-decadal timescales. Both these climate parameters reflect the Atlantic Multi-decadal Oscillation (Schlesinger and Ramankutty 1994) in this region. Therefore, we were unable to separate their respective impacts on the Helheim Glacier variability.

At sub-decadal timescales (3 to 10 years), calving peaks correlated with short-term episodes of positive Shelf index and negative NAO index. As previously mentioned a negative NAO phase is often associated with a warm subpolar gyre and increased penetration of Atlantic water on the shelf (Holland et al. 2008), but local wind and air temperatures as well as variability in both the Polar water and Atlantic water source regions also often co-vary with the NAO index on these timescales (Dickson et al. 2000).

The most important finding from this study is that the increase in calving activity observed at Helheim Glacier during the period 2000 to 2005 is only matched in magnitude by a calving event in the late 1930s (Fig. 2). These two episodes are distinct from other calving episodes in our record. This is because they are the only two events that occur during a time interval characterized by the coincidence of a positive (warm) AMO phase, exceptional (for the investigated time period) high summer temperatures, and low Polar water export. The NAO Index was also frequently negative in the late 1930s, though not markedly more negative than during many of the other calving episodes.

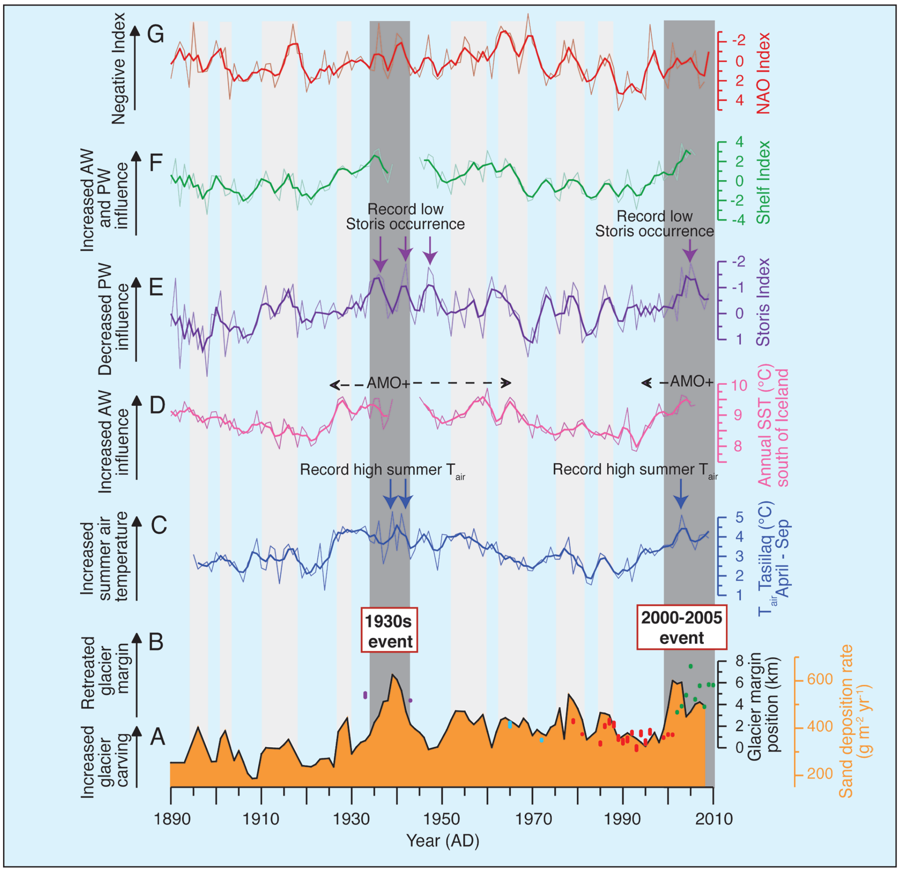

*Figure 2: Comparison between the calving record and climate indices for Helheim Glacier (note the lack of some climate data during the 2nd World War). **A)** Reconstructed calving record of Helheim Glacier from the three sediment cores (Thick lines are 3-year running mean data and thin lines are unfiltered data), **(B)** Helheim Glacier margin positions indicated relative to the 1993 position according to aerial and satellite images (color coding as in Fig.1C), **(C)** summer T_{air} from Cappelen (1995), **(D)** SST south of Iceland (Andresen et al. 2012), **(E)** Storis Index (northernmost multi-year sea ice extent observed off southwest Greenland) from Schmith and Hansen (2003) and updated for 2000-2007 in Andresen et al. (2012), **(F)** Shelf Index (Andresen et al. 2012) and **(G)** NAO data from www.cru.uea.ac.uk/cru/data/nao. (Note AW =Atlantic Water and PW= Polar Water). Figure modified from Andresen et al. (2012).*

Summary

Our study of three sediment cores from the Sermilik Fjord shows that Helheim Glacier responds to changes in large-scale atmospheric and oceanic conditions on timescales as short as a few years. The magnitude of the increase in calving activity observed at Helheim Glacier from 2000 to 2005 is only comparable to a calving episode that occurred in the late 1930s. A comprehensive understanding of the timescales involved in glacier changes and of the influence of oceans and atmospheric variability is important, if we are to make reliable predictions of future glacier changes and associated sea-level rise in a warming world.

Acknowledgements

This study has been financially supported by Geocenter Denmark and the SEDIMICE project, the Danish Council for Independent Research - Nature and Universe (Grant no. 09-064954/FNU), the Danish Agency for Science, Technology and Innovation as a part of the Greenland Climate Research Centre and NSF ARC 0909373.

The reconstructed Helheim glacier calving record can be downloaded from the Pangaea database.

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