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Reconstructing Greenland ice sheet runoff using coralline algae

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ABSTRACT

The Greenland ice sheet (GrIS) contains the largest store of fresh water in the Northern Hemisphere, equivalent to ~7.4 m of eustatic sea-level rise, but its impacts on current, past, and future sea level, ocean circulation, and European climate are poorly understood. Previous estimates of GrIS melt, from 26 yr of satellite observations and temperature-driven melt models over 48 yr, show increasing melt trends. There are, however, no runoff data of comparable duration with which to validate the relationship between the spatial extent of melting and runoff or temperature-based runoff models. Further, longer runoff records are needed to extend the melt pattern of Greenland to centennial timescales, enabling recent observations and trends to be put into a better historical context. We have developed a new GrIS runoff proxy by extracting information on relative salinity changes from annual growth bands of red coralline algae. We observed significant negative relationships between historic runoff, relative salinity, and marine summer temperature in Søndre Strømfjord, Greenland. We produce the first reconstruction of runoff from a section of the GrIS that discharges into Søndre Strømfjord over several decades (1939–2002) and record a trend of increasing reconstructed runoff since the mid 1980s. In situ summer marine temperatures followed an equivalent trend. We suggest that since A.D. 1939, atmospheric temperatures have been important in forcing runoff. These results show that our technique has significant potential to enhance understanding of runoff from large ice sheets as it will enable melt reconstruction over centennial to millennial timescales.

INTRODUCTION

Mass changes of the Greenland ice sheet (GrIS) can affect global sea levels, the strength of the thermohaline circulation (THC) (Rahmstorf and Ganopolski, 1999), and can influence Arctic climate and related feedbacks (Fichefet et al., 2003). For example, during the Holocene, glacial freshwater inflows into the North Atlantic Ocean are thought to have caused perturbations to the THC, leading to onset of Younger Dryas cooling, the 8.2 k.y. event, and the Little Ice Age, with consequent impacts on marine ecosystems, fisheries, and agriculture (Clark et al., 2002; Grove, 1988). Warming over Greenland by the end of the current century is estimated at up to three times the global average (IPCC, 2007) on account of its geographic position. Therefore, modeling the future strength of the THC, and its associated climatic consequences, depends greatly on understanding past GrIS mass balance (Bougamont et al., 2007).

Recent estimates suggest the GrIS was losing ~50 Gt yr^{-1} (Shepherd and Wingham, 2007) during the 1990s, and that since 2006 this rate has increased to an average value of ~270 Gt yr^{-1} (van den Broeke et al., 2009). Remote sensing shows that the spatial extent of melting has increased during the past 25 yr (Fettweis et al., 2007), and there has also been widespread glacier acceleration below 70°N since 2005 (Rignot and Kanagaratnam, 2006). Modeled data indicate a rising trend of annual melt (Hanna et al., 2005; Hanna et al., 2008) and runoff (Ettema et al., 2009; Mernild et al., 2011) over the past 50–60 yr, with record melt years occurring since 2003 (Fettweis et al., 2011; Hanna et al., 2008). These changes in ice melt are likely to have been driven by atmospheric processes and albedo rather than by ocean temperature (Hanna et al., 2009; Tedesco et al., 2011).

As meltwater runoff is estimated to contribute ~50% of Greenland's annual ablation (Box et al., 2006), reconstructing runoff provides an important component in estimating past changes in GrIS ablation. Historic records of changes in the GrIS are needed to assess whether recent runoff trends represent a step change or are natural oscillations about a long-term mean. However, at present only short temporal records are available. In contrast, melt rate records in the Alps have been extended to cover the past century and, for 30 Swiss glaciers, indicate a negative correlation between glacier melt and the Atlantic Multidecadal Oscillation (Huss et al., 2010).

Since the early 1900s, both North Atlantic atmospheric (IPCC, 2007) and marine (Kamenos, 2010) temperatures have increased, so this timescale is also useful for developing and testing methods to reconstruct GrIS melt and runoff at centennial timescales. Here we demonstrate the use of red coralline algae in reconstructing relative salinity and temperature within a Greenland fjord and present the first 63-yr-long reconstruction of historic GrIS melt runoff. We provide the first mechanism that will enable reconstruction of historic changes in GrIS melt runoff at centennial to millennial temporal scales.

MATERIALS AND METHODS

Red coralline algae are long-lived (<700 yr; Frantz et al., 2005) marine algae with slow growth rates (0.015–2.5 mm yr^{-1}) (Kamenos et al., 2008), forming encrusting (calcareous coralline algae) or free-living (maerl or rhodolith) growth forms (Fig. 1). The *Lithothamnion glaciale* alga species has been used to produce validated (Kamenos et al., 2009) paleotemperature reconstructions at biweekly (14 d) resolution over 650 yr using Mg/Ca (Kamenos, 2010; Kamenos et al., 2008) and seasonal paleo–cloud cover reconstructions over 96 yr (Burdett et al., 2011). *Lithothamnion glaciale* (Fig. 1) were collected, using scuba, from Søndre Strømfjord, Greenland (Fig. 2; 66°58′17″N, 53°29′43″W, 8 m depth) in 2009. The Kangerlussuaq drainage basin (KDB) is a 66,000 km^2 catchment draining a section of the GrIS that drains into Søndre Strømfjord. Mg/Ca ratios were extracted from each thallus (n = 3) using the techniques in Kamenos (2010) via electron microprobe analysis at the University of Edinburgh (UK). Mg/Ca were converted to temperature by calibrating against Simple Ocean Data Assimilation (SODA; Carton and Giese, 2008) temperatures with the technique used to construct other existing Mg-temperature

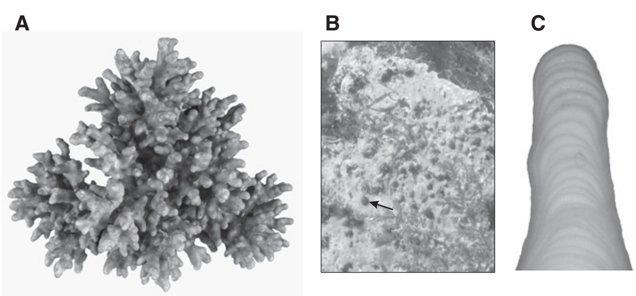

Figure 1. *Lithothamnion glaciale* red coralline algae. A: Example of a free-living thallus (scale bar = 2 cm). B: Encrusting thallus from Søndre Strømfjord (Greenland) with arrow indicating protruding branch (scale bar = 3 cm). C: Transect section through an individual *L. glaciale* branch showing annual growth bands (scale bar = 1 mm).

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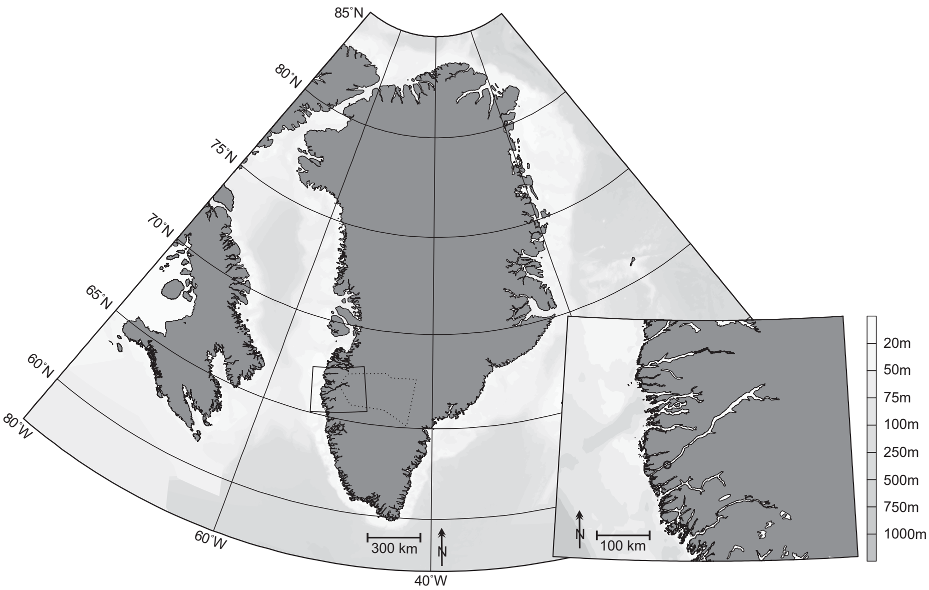

Figure 2. Søndre Strømfjord (inset) in Greenland. Red coralline algal collection site is enclosed in a black circle. Black box on main map indicates location of inset map within Greenland. Area enclosed by dashed line is the Kangerlussuaq drainage basin, which drains into Søndre Strømfjord. Bathymetry is for the open ocean and refers to inset map (data provided by the World Oceanographic Database and plotted using Ocean Data View; Schlitzer, 2012).

relationships (Kamenos, 2010; Kamenos et al., 2008). Mg/Ca were regressed against seasonally corresponding SODA water temperatures at 5 m depth; i.e., Mg/Ca = 0.0122 IST + 0.1026, where Mg/Ca are the molar Mg/Ca ratios in *L. glaciale*, and IST is in situ temperature at 5 m depth (R^2 = 0.88, $p < 0.001$, $SE_b = 5.2 \times 10^{-4}$, $SE_a = 8.4 \times 10^{-3}$ [standard error on gradient b and intercept a]). Summer and winter in situ temperatures were reconstructed between A.D. 1939 and 2002 (see the GSA Data Repository[1] for age model). Growth in the three thalli overlapped between 1939 and 2008 (two of the thalli predated 1939); however, one thallus had a growth inclusion in high-Mg calcite deposited during 2003, so we did not consider any data after 2002 in case the inclusion affected subsequently deposited calcite. Relative salinity was reconstructed using a four-step approach: (1) Mg/Ca-derived temperature was used to calculate predicted δ^{18}O using the *L. glaciale* δ^{18}O-temperature relationship (adjusted for Mg content) (Halfar et al., 2000; Tarutani et al., 1969); (2) microdrilling (New Wave Research) and isotope ratio mass spectrometry (VG Isogas Prism II) at the Scottish Universities Environmental Research Centre (SUERC) were used to determine actual δ^{18}O (which contains both temperature and salinity information; Gagan et al., 1994) at a 5 yr resolution (this resolution proved to be the ideal compromise between material available for analysis and analytical precision); (3) the difference between predicted and actual δ^{18}O is the salinity component of a carbonate record (McCulloch et al., 1994); and (4) the salinity component was converted to relative salinity change using the δ^{18}O-salinity relationship in Alkire et al. (2010).

[1]GSA Data Repository item 2012317, materials and methods, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Proxy Sensitivity

Temperatures derived from Mg/Ca in red coralline algae have a 0.3–0.5 °C error (Kamenos, 2010; Kamenos et al., 2008) against the 6 °C temperature range determined in these samples, representing a low noise-to-signal ratio. Temperature-Mg relationships have been directly calibrated over a 7 yr period (Kamenos et al., 2008) and used to reconstruct temperature over 650 yr (Kamenos, 2010), and, combined with the absence of diagenetic effects (Alexandersson, 1974), are therefore considered temporally stable. Inorganic carbonate exhibits a –0.22 δ^{18}O (‰) per °C rise (Kim and Oneil, 1997) relationship, and seawater exhibits a +0.5 (Broecker, 1989) to +0.7 (Alkire et al., 2010) δ^{18}O (‰) per mil salinity rise relationship. From 1939 to 2002, the Søndre Strømfjord δ^{18}O salinity component had a 3‰ range determined at 0.03‰ analytical precision. Propagation of analytical and regression error generates a total error on calculated salinity of ±0.34 (Fieller's theorem). For full methods, see the Data Repository.

RESULTS AND DISCUSSION

Temperature Relationships

From 1984 to 2002, instrumental summer atmospheric temperature in Kangerlussuaq rose from 8.5 to 10.2 °C (Fig. 3A). There is a significant negative correlation between instrumental atmospheric summer temperature and our reconstructed marine summer in situ temperature in Søndre Strømfjord (Fig. 3F) (r = –0.496, p = 0.031, n = 19). Higher atmospheric temperatures enhance summer melting and runoff (Hanna et al., 2008) into Søndre Strømfjord. This influx of cold runoff (at ~1 °C) likely causes a fall in Søndre Strømfjord seawater temperature, explaining the negative correlation. The relationship between atmospheric and reconstructed marine summer temperature is thus mediated by runoff, explaining the lower-strength (but significant) correlation between them.

Runoff Relationships

The increased cold freshwater input in summer is related to salinity reduction in Søndre Strømfjord (Nielsen et al., 2010) and is demonstrated temporally in this study (Fig. 3). Runoff entering Søndre Strømfjord is mixed within the top 50–75 m of the water column by tidal action at 90 km from the inland fjord terminus, leading to a fall in water salinity (Nielsen et al., 2010). As the sampling location used in this study (Fig. 2) was within the fully mixed portion of Søndre Strømfjord, relative salinity recorded in the growth bands of red coralline algae was used to reconstruct KDB runoff. Differential mixing caused by freshwater discharge variation is not present shallower than 20 m (Nielsen et al., 2010), thus our record is not likely to show changes in mixing patterns but rather runoff-induced changes in surface salinity.

A significant negative correlation between modeled GrIS runoff (r = –0.698, p = 0.037, n = 9) and our reconstructed Søndre Strømfjord salinity (binned to the same 5 yr temporal resolution as relative salinity) was present. While modeled KDB runoff (Fig. 3B) is not long enough to allow robust statistical comparison, there is a clear rise in runoff after 1992 associated with a synchronous fall in reconstructed relative salinity. Drainage area calculations (P. Palmer, 2010, personal commun.) indicate that only a minor portion of runoff is generated by snow melt, and thus we attribute the relative salinity signal to glacial rather than snow origin. There are no tidal glaciers in Søndre Strømfjord; thus calving does not affect fjord salinity.

KDB Runoff Variability and Melt Extent

Our reconstruction indicates that salinity in Søndre Strømfjord peaked during 1984–1988 (Fig. 3C). Our data, comparisons with modeled runoff, and other research (Nielsen et al., 2010), indicate that runoff is a key factor controlling salinity in Søndre Strømfjord, and thus we suggest that, in the period 1939–2002, KDB runoff reached its lowest volume during 1984–1988, and subsequently rose to its highest volume in 2002 (Fig. 3C). Increased melt and runoff has

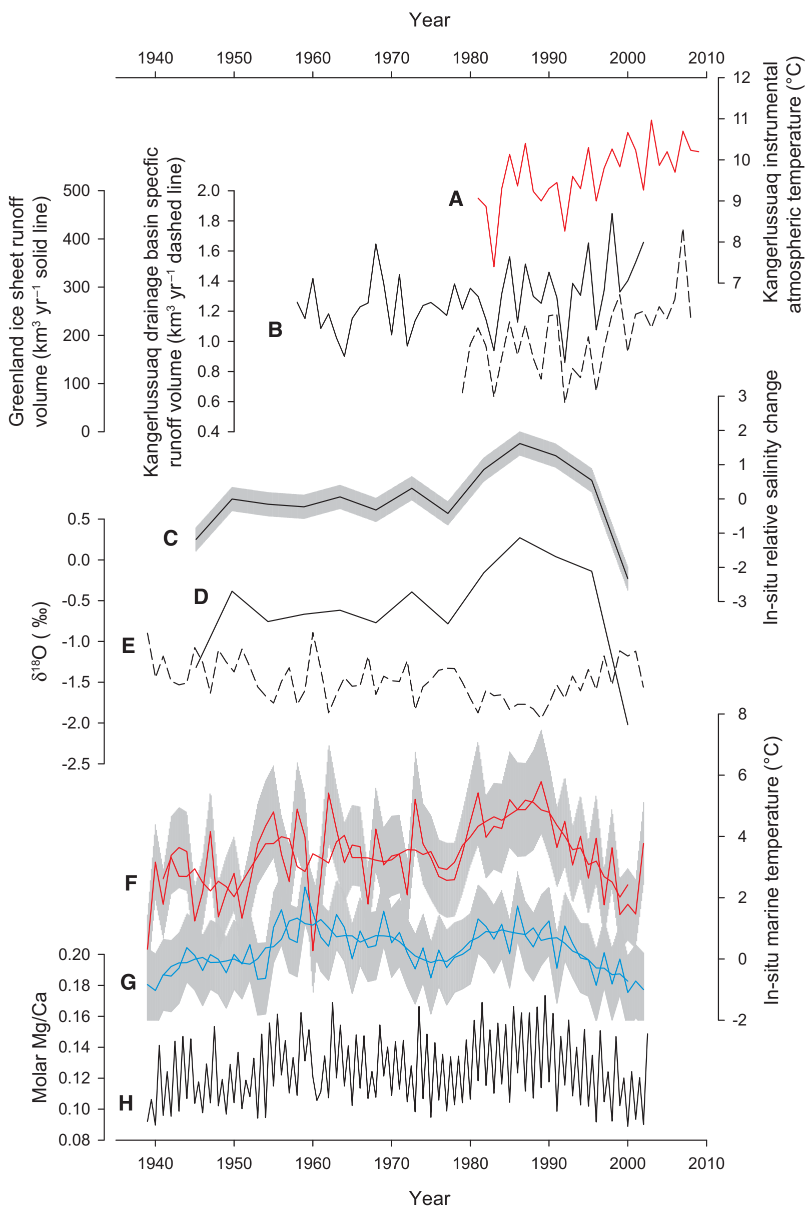

Figure 3. Søndre Strømfjord (Greenland) environmental time series. A: Kangerlussuaq (IWMO station 4231) summer instrumental atmospheric temperature. B: Modeled Kangerlussuaq drainage basin (Mernild et al., 2011) and Greenland ice sheet (Hanna et al., 2008) runoff. C: Relative in situ marine salinity (5 yr bins) at –5 m chart datum in Søndre Strømfjord reconstructed from *Lithothamnion glaciale*. This is negatively correlated to runoff from the Kangerlussuaq drainage basin. Gray shading indicates measurement and regression absolute salinity error. D: $\delta^{18}O$ recorded within the growth banding of *L. glaciale* (5 yr bins). E: Calculated summer $\delta^{18}O$ using temperature derived from F. F: Maximum annual summer temperatures (and 5 yr moving average) at –5 m chart datum in Søndre Strømfjord reconstructed from *L. glaciale*. Gray shading indicates measurement and regression standard error. G: Minimum annual winter temperatures (and 5 yr moving average) at –5 m chart datum in Søndre Strømfjord reconstructed from *L. glaciale*. Gray shading indicates measurement and regression standard error. H: Molar Mg/Ca extracted from *L. glaciale*. Peaks represent maximum summer Mg/Ca and troughs represent minimum winter Mg/Ca.

continued since 2002 with several extreme summer events during 2002–2010 (Ettema et al., 2009; Fettweis et al., 2011; Hanna et al., 2008).

Modeled KDB (Mernild et al., 2011) and GrIS (Hanna et al., 2008) runoff (Fig. 3B) also increase since ca. 1995, in agreement with our KDB record. However, modeled runoff (KDB and GrIS) does not show the distinct drop in runoff volume during 1984–1988 that our reconstruction presents. The difference between reconstructed relative salinity and modeled runoff may be attributed to the high resolution of our proxy allowing identification of this drop, temporally variable model error, and/or a shift in the runoff-ablation balance. To pinpoint the exact causes of the difference we require a longer time series of runoff enabling us to better understand melting behavior.

Søndre Strømfjord In Situ Water Temperature Variability

Mean in situ summer and winter water temperatures in Søndre Strømfjord were dominated by peaks in the 1950s and 1980s (Figs. 3F and 3G). Rates of in situ temperature change were faster in summer than winter during both pronounced upward (1977–1989: $F = 4.21$, $p = 0.04$, $df = 1$; where F is the test statistic and df is degrees of freedom) and downward (1989–2002: $F = 4.56$, $p < 0.001$, $df = 1$) changes in temperature (Figs. 3F and 3G). These results suggest that summer in situ water temperature was most responsible for driving the difference between summer and winter water temperatures; i.e., summer in situ temperatures increased more than winter in situ temperatures. By contrast, instrumental atmospheric records indicate warming winters on the west coast of Greenland since 1873 (Box et al., 2010). We attribute the opposing patterns to our reconstruction recording the influence of meltwater runoff during summer, but during winter recording background fjord water temperature when there is no runoff and Søndre Strømfjord is ice-covered. Thus, as warm winter temperatures enhance melt and runoff the following summer by reducing the energy required to melt accumulated ice and snow (Box et al., 2010), our reconstruction of enhanced summer runoff corroborates those observations. Similarly to this reconstruction, enhanced marine summer warming has also been observed in East Atlantic waters over centennial timescales and attributed to possible differential forcing by the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation on water temperatures in summer and winter (Kamenos, 2010).

While changes in subsurface currents along the west coast of Greenland have been linked to enhanced velocities of tidewater glaciers in Disko Bay at annual timescales (Holland et al., 2008), we observed no evidence of warm water encroachment into Søndre Strømfjord at annual or subannual timescales. During years of warm subsurface ocean temperature (1997–2002) (Holland et al., 2008), our reconstructed in situ water temperatures in Søndre Strømfjord were among the lowest temperatures recorded since 1939 (Fig. 3). Thus, water temperatures in Søndre Strømfjord appear to be controlled by meltwater from the KDB, rather than encroaching water from subsurface ocean currents on the west coast of Greenland.

CONCLUSIONS

We have developed a proxy that for the first time has enabled synchronous reconstruction of temperature in Søndre Strømfjord and runoff from the KDB sector of the GrIS since 1939.

This new proxy will enable the first reconstructions of changes in GrIS runoff during periods of known environmental change such as the Medieval Warm Period. Such events are characterized by large deviations from the mean temperature of the time, and thus the sensitivity of our proxy is well suited to assess whether recently observed changes in GrIS runoff represent a step change or are natural interannual oscillations in runoff reflecting climatic fluctuations and/or ice sheet hydrology.

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