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Winter temperature conditions (1670–2010) reconstructed from varved sediments, western Canadian High Arctic

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ABSTRACT

Advances in paleoclimatology from the Arctic have provided insights into long-term climate conditions. However, while past annual and summer temperature have received considerable research attention, comparatively little is known about winter paleoclimate. Arctic winter is of special interest as it is the season with the highest sensitivity to climate change, and because it differs substantially from summer and annual measures. Therefore, information about past changes in winter climate is key to improve our knowledge of past forced climate variability and to reduce uncertainty in climate projections. In this context, Arctic lakes with snowmelt-fed catchments are excellent potential winter climate archives. They respond strongly to snowmelt-induced runoff, and indirectly to winter temperature and snowfall conditions. To date, only a few well-calibrated lake sediment records exist, which appear to reflect site-specific responses with differing reconstructions. This limits the possibility to resolve large-scale winter climate change prior the instrumental period.

Here, we present a well-calibrated quantitative temperature and snowfall record for the extended winter season (November through March; NDJFM) from Chevalier Bay (Melville Island, NWT, Canadian Arctic) back to CE 1670. The coastal embayment has a large catchment influenced by nival terrestrial processes, which leads to high sedimentation rates and annual sedimentary structures (varves). Using detailed microstratigraphic analysis from two sediment cores and supported by µ-XRF data, we separated the nival sedimentary units (spring snowmelt) from the rainfall units (summer) and identified subaqueous slumps. Statistical correlation analysis between the proxy data and monthly climate variables reveals that the thickness of the nival units can be used to predict winter temperature ($r = 0.71$, $p_c < 0.01$, 5-yr filter) and snowfall ($r = 0.65$, $p_c < 0.01$, 5-yr filter) for the western Canadian High Arctic over the last ca. 400 years. Results reveal a strong variability in winter temperature back to CE 1670 with the coldest decades reconstructed for the period CE 1800–1880, while the warmest decades and major trends are reconstructed for the period CE 1880–1930 (0.26°C/decade) and CE 1970–2010 (0.37°C/decade). Although the first aim of this study was to increase the paleoclimate data coverage for the winter season, the record from Chevalier Bay also holds great potential for more applied climate research such as data-model comparisons and proxy–data assimilation in climate model simulations.

1. Introduction

The Arctic is recognized as one of the most sensitive regions to climate change (ACIA, 2004; Collins et al., 2013). Amplified warming of the Arctic climate has long been demonstrated from both observations and simulations (Hardy et al., 1996; Moritz et al., 2002; Miller et al., 2010; Comiso and Hall, 2014). This warming has led to increases in high-latitude precipitation that are particularly notable during the winter season (Kattsov and Walsh, 2000; Bintanja and Selten, 2014).

Arctic warming has been considered unprecedented over the past thousand years based on available paleoclimate data. Information about past climate variability is essential to assess the sensitivity of the Earth's climate to natural and anthropogenic forcings, and to reduce uncertainty in future climate projections (Masson-Delmotte et al., 2013). For the Arctic, the most comprehensive studies of climate change assessment covered the past four centuries (Overpeck et al., 1997), the last two millennia (Kaufman, 2009; McKay and Kaufman, 2014), and the Holocene (Sundqvist

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et al., 2014; Briner et al., 2016).

However, while most of the paleoclimate records in the Arctic are related to annual and summer temperature (Briner et al., 2016), comparatively little has been reported about winter paleoclimate (e.g. Cuven et al., 2011). As an example, only four winter reconstructions out of over fifty-six records were considered in the extended database used to reconstruct Arctic temperatures by McKay and Kaufman (2014). As a result, seasonality is hardly considered in climate models, especially regarding the winter season (Goosse et al., 2010). Winter climate is of particular interest because it is the season with the highest sensitivity to climate change (Thompson and Wallace, 1998; Rinke et al., 1999; Moritz et al., 2002), which greatly differs from summer and annual measures (Jones et al., 2014). Therefore, information about past changes in winter climate is required in order to reduce uncertainty in large-scale assessments of climate variability and change.

In this context, Arctic lakes and similar sedimentary settings are excellent potential climate archives owing to their capacity to preserve climate variability through very long times and at a high temporal resolution (Hughen et al., 1996). Moreover, these Arctic environments provide very specific and advantageous settings such as a strong sensitivity to extreme seasonal variations in processes (stream flow and sediment delivery), and limited direct human impact (Smol and Douglas, 1996; Lamoureux and Gilbert, 2004). In particular, Arctic lakes with nival catchments were shown to respond directly to the length and the intensity of the snowmelt, and indirectly to winter temperature and snowfall conditions on the previous year (Forbes and Lamoureux, 2005; Cockburn and Lamoureux, 2008).

Nevertheless, reconstructing past climate from Arctic lakes remains an analytical challenge. For instance, low ^{210}Pb inventories and the paucity of degradable-terrestrial remains limit ^{210}Pb and ^{14}C dating, respectively (Wolfe et al., 2004). Moreover, low sedimentation accumulation rates in some Arctic lakes may restrict the temporal resolution and the length of the paleoclimate records. This is the reason why annually laminated sediments (varves) have received a growing scientific attention over the past two decades. Varved sediments are recognised as a useful tool for Arctic paleoclimatology (Hughen et al., 1996), which have provided successful paleoclimate examples from the Canadian High Arctic (Wolf and Smith, 2004; Besonen et al., 2008).

To date, only a few annually-resolved and well-calibrated sediment records exist for the winter season (e.g. Cuven et al., 2011). Moreover, results from individual records suggest a strong sensitivity to: (i) local changes in winter climate; and (ii) specific catchment properties and snowmelt response. This local focus has resulted in a great diversity among the records, with typical examples such as: June temperature (Hughen et al., 2000), August-to-October temperature and snowfall (Tomkins et al., 2010), snowmelt intensity (Francus et al., 2002), and September-to-May temperature and May snow depth (Cuven et al., 2011). These differences in the records clearly limit the possibility to resolve large-scale and regional patterns of winter climate change prior the instrumental period.

Here, we present a well-calibrated quantitative temperature record for the extended winter season (November through March; NDJFM), which is representative of a large part of the Canadian High Arctic. Using detailed microstratigraphical analysis supported by an annual chronology, we demonstrate that the relatively thick varves from Chevalier Bay (Melville Island, NWT) contain a winter temperature signal, which can be reconstructed for the past ca. 400 years. With this paleoclimate record, we demonstrate that the indirect information stored in the winter temperature and snowfall conditions holds great potential for more advanced application in climate research.

2. Study site

Chevalier Bay (75°03′10″N, 111°30′38″W; unofficial name) is a coastal marine setting located on Melville Island, Dundas Peninsula, Northwest Territories in the Canadian High Arctic. The bay is located about 50 km west from the Cape Bounty Arctic Watershed Observatory (CBAWO; Fig. 1a); a research site where hydrological, sediment transport and lake deposition studies have been undertaken since 2003. Chevalier Bay is a small marine embayment that is largely isolated from the ocean and marked by a sedimentary environment similar to a coastal lacustrine basin. The catchment is strongly influenced by terrestrial processes and can be regarded as a nival catchment (Cockburn and Lamoureux, 2008), enabling the sediment record from Chevalier Bay to be compared with other Arctic nival-lake sediment records. Of particular interest, its catchment has a remarkably large area (350 km^2); 152 times larger than the area of the bay (Fig. 1b). This catchment feature leads to high sedimentation rates (mean 2.53 mm yr^{-1}), atypical of other studied Arctic sites (common annual rates range from 0.2 to 1 mm; e.g. Tomkins et al., 2010; Francus et al., 2002; respectively).

The bedrock of the area consists of folded Devonian iron-rich weathered sandstone and siltstone (Hodgson et al., 1984; Christie and McMillan, 1994). The landscape features a limited relief (max. 110 m a.s.l.) with the drainage system developing on sparse tundra vegetation and continuous permafrost (Fig. 1b).

The climate of the region is classified as polar desert (tundra climate *ETf*; Köppen-Geiger classification) characterized by cold winters, cool summers, and limited annual precipitation that falls primarily as snow during the autumn/winter season (Fig. 1c). Mean summer (JJA) and extended winter (NDJFM) temperatures are 3.5°C and −27.8°C, respectively (CE 1949–1997; Mould Bay meteorological station, 280 km to the west; Fig. 1). Annual precipitation is dominated by winter snowfall leading to a maximum mean snow accumulation of 300 mm depth in early May, while rare high-intensity rainfall events (>10 mm/day) occur in summer (Fig. 1c). Total annual precipitation amounts to 98 mm.

Chevalier Bay is at sea level and connected to the Arctic Ocean by an estimated 7-m deep narrow inlet, enabling tidal interaction during the short ice-free period (July-August to early October). Properties of the 16-m deep water-column of Chevalier Bay were measured in June 2010 (Fig. 2). It reveals two chemoclines at 3 and 7 m depth, with the hypolimnion characterised by quasi-anoxic conditions (<10% saturation) and saline water of 35 PSU. In spring, snowmelt-induced freshwater enters the lake under the ice cover (~2-m thick), which is marked by low salinity (4 PSU), a peak in turbidity (58 NTU), warmer temperature (1°C), and high dissolved oxygen content (85% saturation).

3. Material and methods

The study of snowmelt-induced processes and the relationship between stream discharge and suspended sediment transport could not be conducted at Chevalier Bay. However, such research was undertaken at nearby West and East Lakes in CBAWO (Fig. 1a), and will be used for comparison and correlation. This nearby site has similar hydroclimate, topography, surface materials, vegetation and geology (Cockburn and Lamoureux, 2008; Lewis et al., 2012).

3.1. Sediment coring and processing

Two sediment cores were retrieved from Chevalier Bay in June 2010 with a Universal gravity-percussion corer (Aquatic Research Instruments); one from the middle (10CV03, 86 cm long), and another from a more proximal location (10CV04, 46 cm long) (Fig. 1b). The comparison between these two cores was used to: (i)