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Episodic Neoglacial snowline descent and glacier expansion on Svalbard reconstructed from the ^{14}C ages of ice-entombed plants

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A B S T R A C T

The response of the Northern Hemisphere cryosphere to the monotonic decline in summer insolation and variable radiative forcing during the Holocene has been one of irregular expansion culminating in the Little Ice Age, when most glaciers attained their maximum late Holocene dimensions. Although periods of intervening still-stand or ice-retreat can be reconstructed by direct dating of ice-recessional features, defining times of Neoglacial ice growth has been limited to indirect proxies preserved in distal archives. Here we report 45 precise radiocarbon dates on *in situ* plants emerging from beneath receding glaciers on Svalbard that directly date the onset of snowline descent and glacier expansion, entombing the plants. Persistent snowline lowering occurred between 4.0 and 3.4 ka, but with little additional persistent lowering until early in the first millennium AD. Populations of individual ^{14}C calendar age results and their aggregate calendar age probabilities define discrete episodes of vegetation kill and snowline lowering 240–340 AD, 410–540 AD and 670–750 AD, each with a lower snowline than the preceding episode, followed by additional snowline lowering between 1000 and 1220 AD, and between 1300 and 1450 AD. Snowline changes after 1450 AD, including the maximum ice extent of the Little Ice Age are not resolved by our collections, although snowlines remained lower than their 1450 AD level until the onset of modern warming. A time-distance diagram derived from a 250-m-long transect of dated ice-killed plants documents ice-margin advances ~750, ~1100 and after ~1500 AD, concordant with distributed vegetation kill ages seen in the aggregate data set, supporting our central thesis that vegetation kill ages provide direct evidence of snowline lowering and cryospheric expansion. The mid- to late-Holocene history of snowline lowering on Svalbard is similar to ELA reconstructions of Norwegian and Svalbard cirque glaciers, and consistent with a cryospheric response to the secular decline of regional summertime insolation and stepped changes in nearby surface ocean environments. The widespread exposure of entombed plants dating from the first millennium AD suggests that Svalbard's average summer temperatures of the past century now exceed those of any century since at least 700 AD, including medieval times.

1. Introduction

The Svalbard archipelago (Fig. 1) is one of the most northerly island groups in the Northern Hemisphere (NH), with a land surface that is presently ~60% glaciated (Hagen et al., 1993). During the Last Glacial Maximum (~21 ka) ice extended onto the adjacent continental shelves and the subsequent deglaciation history has been relatively well documented based on a combination of glacial and marine geologic studies (Landvik et al., 1998). However, the record of more recent Late Holocene climate history and associated ice cap and glacier variation remains fragmentary, in large part because most Svalbard glaciers reached their maximum Neoglacial

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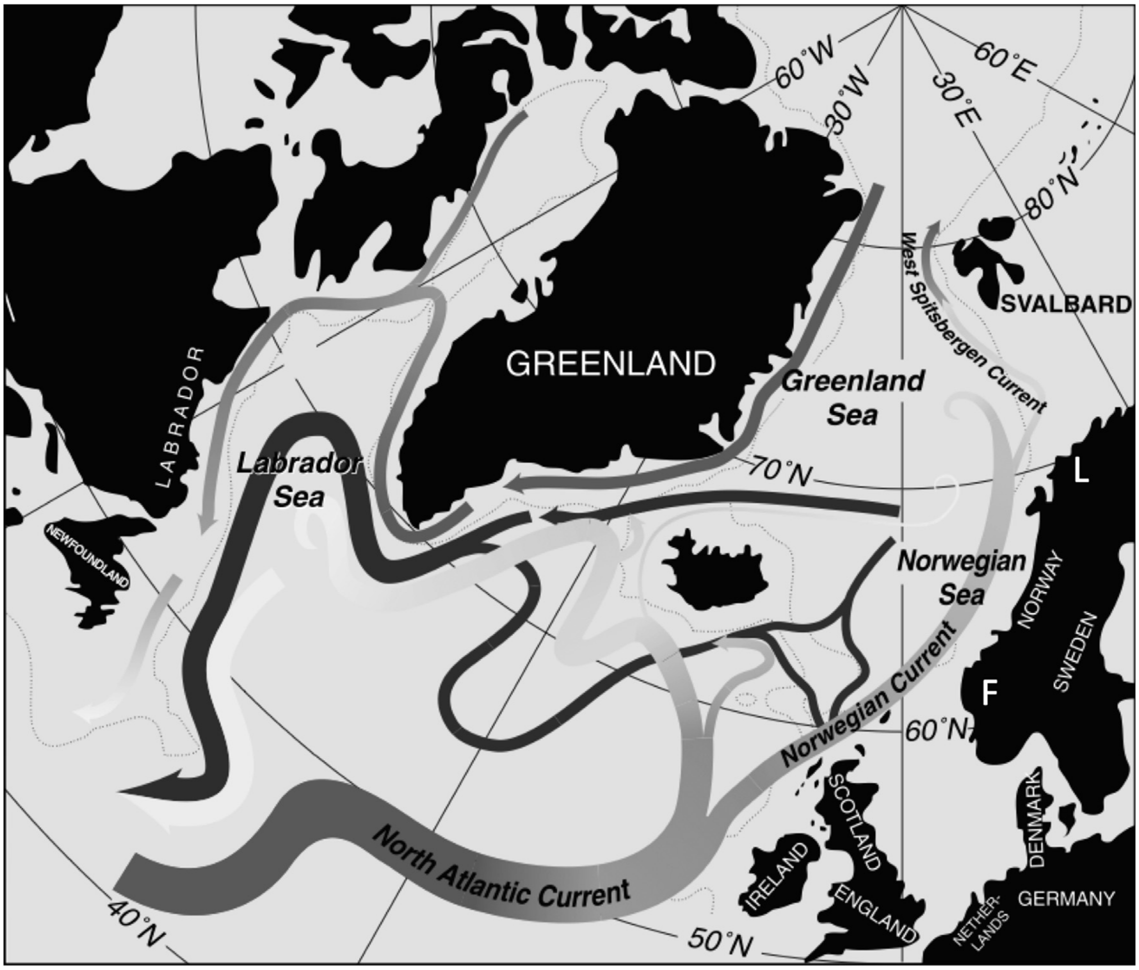

Fig. 1. Northern North Atlantic region, showing the location of Svalbard and major North Atlantic surface currents; warm surface currents (light tones), cold surface currents (darker tones), deep currents (darkest tones). L: Lenangsbreene; F: Folgefonna. Modified from (McCartney et al., 1996).

extent during the Little Ice Age (LIA; Svendsen and Mangerud, 1997) removing evidence of earlier advances. Rare remnant lateral moraines indicate multiple Neoglacial advances, but dating moraine formation has proven to be challenging. Werner (1993) used lichenometry to provide approximate ages on nested Neoglacial moraines fronting Svalbard glaciers, documenting at least four advances, with moraine stabilization ~1.5 ka, ~1.0 ka, ~0.6 ka and around the end of the 19th Century. Cosmogenic radionuclides in boulders from a remnant lateral moraine on Spitsbergen suggest moraine stabilization there at about 1.6 ka (Reusche et al., 2014), although ages were highly variable indicating that they may have been influenced by nuclide inheritance and post-depositional rotation of moraine boulders. Changes in Svalbard glacier activity also has been inferred from diagnostic proxies preserved in glacier-dominated lake sediments (Svendsen and Mangerud, 1997; Snyder et al., 2000b; Røthe et al., 2015), indicating Neoglaciation began ~5 ka, with local glaciers reaching maximum dimensions in the LIA.

Repeat aerial and satellite surveys of Svalbard glaciers document significant lateral glacier retreat since their LIA maximum (Hagen et al., 2003), with an estimated further reduction of glacierized area of ~7% in the last ~30 years (Nuth et al., 2013). Retreat of Svalbard glaciers coincides with an interval of rising summer temperatures, which have increased locally by more than 0.5 °C per decade since 1980 (Fig. 2). In parts of western Svalbard, glacier retreat appears to have been aggravated by upland ice cap thinning attributable to a recent decrease in winter-time precipitation (James et al., 2012). The temperature of the Svalbard Archipelago is maintained well above the zonal average by the presence of the warm, poleward flowing West Spitsbergen Current (WSC), a northerly extension of the North Atlantic Current (Fig. 1) related in part to the Atlantic Meridional Overturning Circulation (AMOC). The associated heat transport results in mean annual surface air temperatures (MAT) over Svalbard that are ~10 °C higher than over NE Greenland, <500 km distant at the same latitude. Earlier studies have noted a correlation between the instrumental MAT record over the Arctic (Chylek et al., 2009) and Svalbard (Humlum et al., 2011) and the Atlantic Multi-decadal Oscillation (AMO) index, a basin-wide average of North Atlantic sea surface temperature (SST), thought to represent a response to internal or forced variability of the AMOC and changes in the bulk planetary radiative forcing (Hurrell and Deser, 2010). We note a zero-lag correlation of the record of yearly summertime Svalbard temperature (Fig. 2) and the AMO since 1899 of 0.42, but a substantially larger correlation ($R = 0.60$) with the record of annual average extra-tropical Northern Hemisphere temperature (of which the local record is only a very small part). This, together with the fact that indices of AMOC strength have declined in recent decades (Rahmstorf et al., 2015) while Svalbard temperatures have continued to rise, suggest that local temperatures are substantially influenced by altered radiative forcing in addition to variable ocean heat transport. On longer timescales, the regular decline in local summer insolation receipts also influenced Arctic temperature and ice extent through