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# Early start of 20th-century Arctic sea-ice decline recorded in Svalbard coralline algae

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## ABSTRACT

**The fast decline of Arctic sea ice is a leading indicator of ongoing global climate change and is receiving substantial public and scientific attention. Projections suggest that Arctic summer sea ice may virtually disappear within the course of the next 50 or even 30 yr with rapid Arctic warming. However, limited observational records and lack of annual-resolution marine sea-ice proxies hamper the assessment of long-term changes in sea ice, leading to large uncertainties in predictions of its future evolution under global warming. Here, we use long-lived encrusting coralline algae that strongly depend on light availability as a new in situ proxy to reconstruct past variability in the duration of seasonal sea-ice cover. Our data represent the northernmost annual-resolution marine sea-ice reconstruction to date, extending to the early 19th century off Svalbard. Algal records show that the decreasing trend in sea-ice cover in the high Arctic had already started at the beginning of the 20th century, earlier than previously reported from sea-ice reconstructions based on terrestrial archives. Our data further suggest that, although sea-ice extent varies on multidecadal time scales, the lowest sea-ice values within the past 200 yr occurred at the end of the 20th century.**

## INTRODUCTION

During the past four decades, the time period for which satellite measurements are available, summer sea-ice cover in the Arctic Ocean has declined by >10% per decade (Walsh et al., 2017). Climate models have not only failed to predict the speed and extent of the observed Arctic sea-ice decline because uncertainties in sea-ice modeling are large (Rampal et al., 2011), they also significantly underestimate recent high-latitude surface warming (Boé et al., 2009) (Fig. 1). Although the loss of Arctic sea ice is visible for all months and in all regions, it varies substantially between regions and time of year (Cavalieri and Parkinson, 2012). Thus, it is important to understand the various forcings that contribute to the loss of Arctic sea ice in different regions.

The West Spitsbergen Current (WSC) carries relatively warm and salty Atlantic waters north into the Arctic Ocean along the western coast of Spitsbergen (Svalbard archipelago; Fig. 1A). Inflow of warmer Atlantic water to the Arctic via the WSC plays a major role in shaping ice conditions, and it has been reported that the temperature of the WSC has increased by ~1 °C since C.E. 1979 (Onarheim et al., 2014), leading to warming of the Arctic Surface Water and the melting of Arctic sea ice. Due to the short duration of satellite records, generally not extending prior to the late 1970s, very little is known about the natural variability of subarctic to arctic North Atlantic surface-ocean temperature and Arctic sea-ice changes on longer time scales (Polyak et al., 2010). This is particularly critical because, in the case of Arctic sea ice, the few available historical time series and reconstructions suggest that the recent observational state of Arctic sea-ice cover is far below the centennial to millennial averages, although large variations may have occurred on longer time scales (Kinnard et al., 2011). Arctic-wide warming since the mid-19th century, coincident with the end of the Little Ice Age, is well documented (Overpeck et al., 1997). However, little is known about the response of sea ice to abrupt warming, and it is presently unclear when the decline in Arctic sea ice started. Previous reconstructions of sea-ice extent, which have been based mainly on indirect terrestrial records such as tree rings, ice cores, and lake sediments, suggest a start of the decline in the second half of the 20th century (Walsh and Chapman, 2001; Kinnard et al., 2011), at around the same time as satellite observations became available. Evidence from a newly developed direct marine sea-ice proxy based on encrusting coralline algae has indicated an earlier start of Arctic sea-ice decline in the Canadian Arctic, with an overall long-term downward trend already beginning in the 1920s (Halfar et al., 2013).

Here, we have developed time series from long-lived Arctic coralline algae that grow attached to the shallow seafloor, with life spans up to 200 yr. This novel, annually resolved, marine sea-ice proxy facilitates for the first time the assessment of long-term sea-ice cover variability in northern Svalbard (for detailed description of the samples and the study site Mosselbukta, see the GSA Data Repository[1]). The genus *Clathromorphum* Foslie, 1898 (Hapalidiales, Rhodophyta) has recently been shown to be well suited as a high-latitude climate recorder because it (1) is widely distributed on the shallow, rocky seafloor (10–25 m depth) of the extratropical Atlantic, Pacific, and Arctic oceans (Adey

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[1]GSA Data Repository item 2019341, supplemental information on sample collection, preparation methods, and analysis, Figure DR1 (spectral analysis of algal time series), and Table DR1 (primary data from Svalbard samples used for calculating the algal sea-ice proxy), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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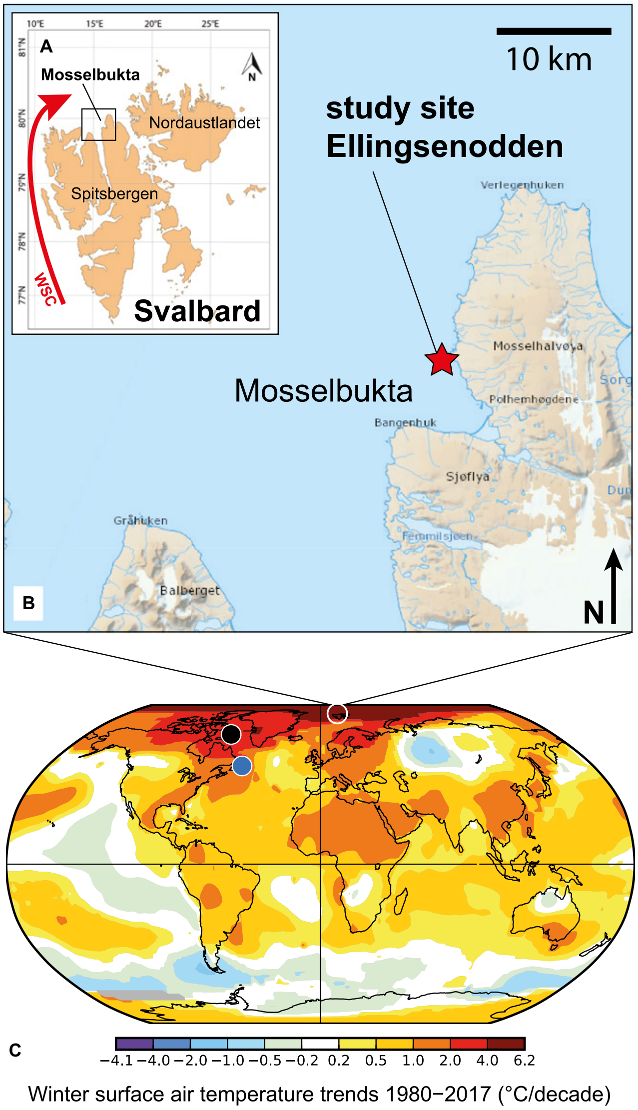


**Figure 1. Study area and surface air temperature trends. (A) Map of Svalbard archipelago in the arctic North Atlantic, with location of Mosselbukta study site in northern Spitsbergen (rectangle, enlarged in B), where long-lived encrusting coralline algal buildups were collected in June 2016. Red arrow indicates approximate path of West Spitsbergen Current (WSC). (B) Detailed shaded-relief map of study site with sampling location Ellingsenodden in Mosselbukta (red asterisk). Source of shaded-relief map: https://toposvalbard.npolar.no/. (C) Global winter surface-air temperature trends since C.E. 1980 (linear trends in °C/decade for December–February). Geographic locations of the Svalbard archipelago (this study, white open circle), Newfoundland, Canada (Hill and Jones [1990] sea-ice record, blue circle), and Labrador–Canadian Arctic (Halfar et al. [2013] algal sea-ice proxy, black circle) are shown. Data source: http://data.giss.nasa.gov/gistemp.**

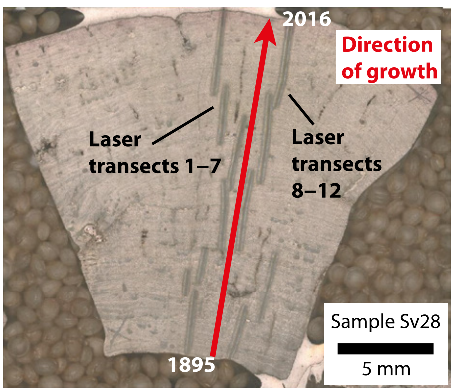


**Figure 2. Sample material. Photomosaic of polished cross section of coralline alga from Mosselbukta, Svalbard (sample Sv28, *Clathromorphum compactum*, C.E. 1895–2016 [time period covered by the proxy]). Post-analysis laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) line transects are visible reaching from top to bottom of the sample. Red arrow indicates direction of algal growth.**

et al., 2013; Jørgensbye and Halfar, 2016), (2) has a multi-century life span, and (3) displays annual growth increments in a high-Mg calcite skeleton (Fig. 2). A number of studies have examined various aspects of the chemical and physical structure of coralline algae in order to reconstruct past changes in large-scale climate patterns affecting the North Pacific and North Atlantic oceans (Halfar et al., 2011b; Kamenos et al., 2012; Hetzinger et al., 2013, 2018; Williams et al., 2018b). Annual growth rates of *Clathromorphum* are dependent on light and temperature (Halfar et al., 2011a). During the ice-free period, photosynthesis in this species is highly efficient and excess photosynthate is stored (Adey et al., 2013). With time under sea-ice cover, the stored photosynthates are exhausted, limiting annual growth. During times of extensive sea-ice cover, little light reaches the seafloor, resulting in low annual growth rates or even a cessation of growth in winter. Thus, the length of the annual open-water interval limits the number of days when significant algal growth can take place. Water temperatures remain relatively constant below sea ice; in turn, more ice-free days allow for higher temperatures, which are recorded in the Mg/Ca ratios of the algae. The effects of both light and temperature on calcification and $MgCO_3$ in *Clathromorphum compactum* (Kjellmann) Foslie (1898) have been confirmed in a recent mesocosm study (Williams et al., 2018a). By using a combination of Mg/Ca ratios and annual algal growth rates from Labrador–Canadian Arctic algae, it has been possible to reconstruct sea-ice conditions back to the 14th century (Halfar et al., 2013), yielding an inverse relationship between algal proxy and sea ice. Our samples represent the first annually resolved *in situ* marine record of sea-ice history for the High Arctic. We compared combined algal growth and Mg/Ca proxy data from northern Svalbard to observed sea-ice data, historical Arctic sea-ice extent and sea-ice edge positions, and proxy-based sea-ice reconstructions. We used spectral analysis of the Svalbard algal proxy record to reveal dominant interannual- to multidecadal-scale variability, and we assess the trends in the algal sea-ice proxy record (detailed methods are provided in the Data Repository).

## RESULTS AND DISCUSSION

Satellite-derived sea-ice records from the Arctic are too short to investigate decadal- and longer-scale variability. The availability of direct sea-ice observations before the satellite era is decreased compared to after. Reconstructed sea-ice data are available from C.E. 1901 onward, with data gaps because gridded data sets of Arctic sea ice are essentially constructed from a limited number of observations (the Hadley Centre Global Sea Ice and Sea Surface Temperature [HadISST] data set; Rayner et al., 2003; Fig. 3A; see also the Data Repository). Algal records from all specimens are significantly inversely correlated to sea-ice concentration (SIC) when compared individually to May–October HadISST (Rayner et al., 2003) ($R > -0.4$ on annual mean scales [$p < 0.01$]; $R > -0.5$ for 5 yr running means, "N5" [$p < 0.05$], 1901–2014). Averaging records from three individual algal specimens, hereafter referred to as the multi-specimen record (common time period: C.E. 1895–2014), improves the relationship to observational SIC data ($R = -0.56$ [N5, $p < 0.05$], $R = -0.64$ [11 yr running means, "N11", $p < 0.05$]). For longer comparisons, i.e., before 1895, we also use the longest-recorded specimen separately (sample Sv1, 1813–2015), referred to as the single-specimen record.

Correlations are calculated using seasonal sea-ice data because these represent the mostly ice-free time period at the study site, although the timing of the start and end of the ice-free season varies from year to year. The May–October

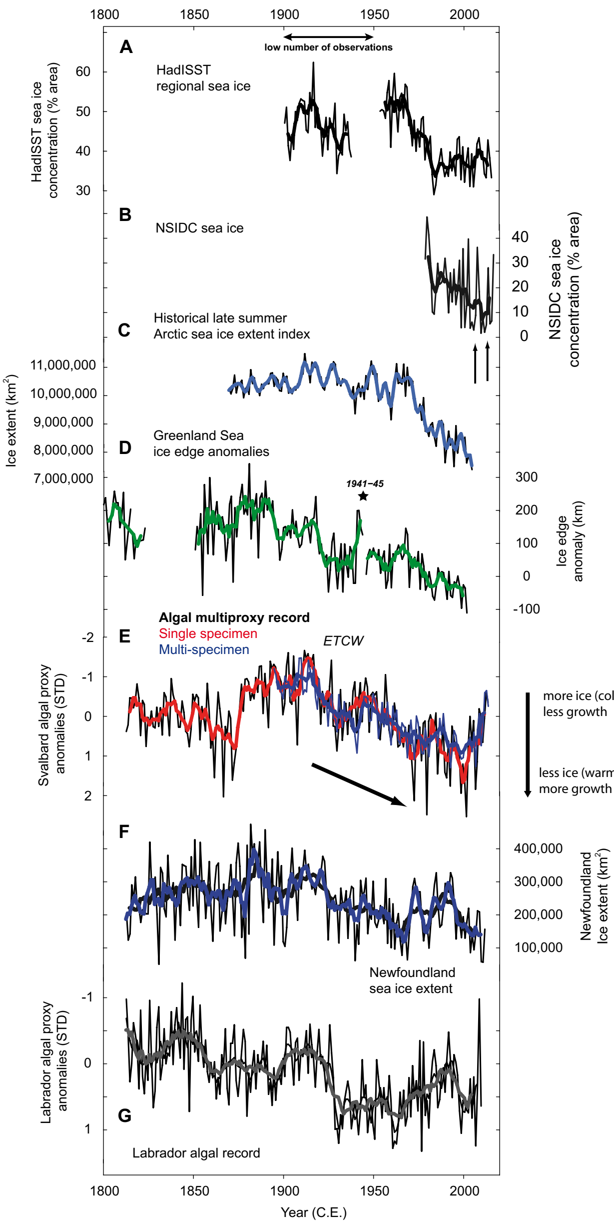


**Figure 3. Algal proxy records compared to sea-ice observations and proxy reconstructions. (A,B) Observational sea-ice concentration data averaged for region including study site (Mosselbukta, Svalbard) derived from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) data set (Rayner et al., 2003) (A) and U.S. National Snow and Ice Data Center (NSIDC) (B) data set (https://nsidc.org) (shown as May–October averages; see Methods in text). Sea-ice concentration is shown as percent area covered by sea ice. Before C.E. 1950, the number of direct sea-ice observations is low, and HadISST values are based largely on climatology rather than real observations. (C) Historical index of late summer (August) Arctic sea-ice extent (Kinnard et al., 2011). (D) Greenland Sea sea-ice edge position anomalies from historical ice observations (Divine and Dick, 2006). Black asterisk marks 1941–1945 time period, where data coverage is limited due to observation gaps during the Second World War. (E) Sea-ice proxy reconstructions from the Svalbard algal multiproxy record (this study), shown as single-specimen (red, based on specimen Sv1; C.E. 1813–2015 [time span covered by the proxy]) and multi-specimen records (blue, averaged from three samples, Sv1, Sv28, and Sv90; 1895–2015). ETCW—early 20th-century warming in the Arctic. Black thick arrow depicts declining trend in Svalbard sea ice since the early 20th century. (F) Newfoundland sea-ice extent (Hill and Jones, 1990). (G) Labrador and Canadian Arctic algal sea-ice proxy record (Halfar et al., 2013). Bold lines represent 5 yr moving averages, and thin black lines represent annual data. Algal proxy records are plotted inversely. Thin vertical black arrows in B mark years where the algal proxy suggests summers with above-average sea ice in the 21st century, concurrent with NSIDC satellite sea-ice observations (summers of 2003, 2008–2010). Algal proxy data are normalized to unit variance by subtracting the mean and dividing by the standard deviation (STD).**

average includes the shoulder periods; i.e., the months where year-to-year variability is strongest based on satellite observations. During the most recent decades, the algal proxy suggests a sharp decline of sea ice from approximately the 1980s (Fig. 3E) to the end of the 20th century, similar to observed sea-ice variability for northern Svalbard (U.S. National Snow and Ice Data Center [NSIDC] data, https://nsidc.org; Fig. 3B), while reconstructed HadISST SIC data show no apparent trend. This may be attributed partly to the different underlying data sets, as well as measurement and reconstruction techniques (e.g., spatial averaging effects and different temporal and spatial resolution). From ca. 2003 onward, a brief decrease (i.e., increase in sea ice) is evident in the algal proxy record. NSIDC data also suggest higher-than-average SICs in the summer months of the years 2003 and 2008–2010 for the study region; i.e., more sea-ice cover during the time period of maximum algal growth (Figs. 3B and 3E).

Historical ice observations available from various sources for the Nordic Seas were used to compile past ice-edge position anomalies back to 1750 (Divine and Dick, 2006). A comparison of our proxy record to sea-ice edge position anomalies for the Greenland Sea region, including our study site (Figs. 3D and 3E), shows a high correspondence, yielding significant inverse relationships for both the single-specimen record (sample Sv1, 1813–2002, $R = -0.61$ [N5, $p < 0.01$], $R = -0.63$ [N11, $p < 0.01$]) and the multi-specimen record (1895–2002, $R = -0.83$ [N5, $p < 0.01$], $R = -0.89$ [N11, $p < 0.01$]). In addition, we compared the algal time series to independent proxy-based sea-ice reconstructions for the Arctic. One of the few available long time series of sea ice is the Newfoundland (eastern Canada) winter sea-ice extent record (Hill and Jones, 1990), which is based on different sources and extends back to 1810. Despite the distance, the High Arctic Svalbard algal proxy is significantly correlated to Newfoundland winter sea-ice extent for both the single-specimen record (sample Sv1, 1813–2012, $R = -0.51$ [N5, $p < 0.01$], $R = -0.65$ [N11, $p < 0.05$]), $R = -0.72$ [N11, 1895–2000, $p < 0.05$]) and the multi-specimen record (1895–2012, $R = -0.67$ [N5, $p < 0.01$], $R = -0.77$ [N11, $p < 0.01$]).

The clear downward trend in Arctic sea-ice extent through the 20th century, as suggested by the algal proxy record, is also observed in the historical Newfoundland winter sea-ice record (Fig. 3F). Both the Greenland Sea ice-edge position record and the Svalbard algal record (Figs. 3D and 3E) suggest a pronounced shift to more sea ice (i.e., more negative algal proxy) at ca. 1870. In the Svalbard algal record, a long-term decreasing sea-ice trend then begins in the early 1910s, synchronous with a decline in Greenland Sea sea-ice edge position, continuing throughout the entire 20th century. The most positive values (i.e., lowest sea ice) occur at ca. 2000, even more positive than the values seen during the 1860s and 1870s (Fig. 3). Our data suggest that the substantial decline of sea ice at Svalbard began with the onset of the early 20th-century warming (ETCW, Fig. 3E), a large Arctic warming event that commenced in the early 1920s and peaked at 1930–1940. This event is pronounced in observed surface-air temperature data, and has been linked to a major increase in westerly winds between Norway and Spitsbergen leading to enhanced atmospheric and oceanic heat transport from the comparatively warm North Atlantic Current to the Arctic (Bengtsson et al., 2004). Thus, the onset of 20th-century sea-ice decline may have started some years earlier at northern Svalbard than in other regions of the Arctic. For example, both the Newfoundland sea-ice extent (Fig. 3F) and the Labrador–Canadian Arctic sea-ice record (Fig. 3G) suggest a drop in sea ice beginning in the mid-1920s. The temperatures of Atlantic water entering the Arctic Ocean with the WSC also had increased at the start of the 20th century (Spielhagen et al., 2011), which may be a possible explanation for the earlier start of the long-term sea-ice decline at Svalbard. Land-based reconstructions such as the historical index of late summer (August) Arctic sea-ice extent (Kinnard et al., 2011) (Fig. 3C; multi-specimen algal record: $R = -0.6$ [annual means, $p < 0.01$], $R = -0.76$ [N11, $p < 0.05$]) suggest a different timing, with a much later onset of the sea-ice decline. An early onset is also supported by an algal-based sea-ice reconstruction for the Canadian Arctic (Halfar et al., 2013), This record (Labrador algal record) is significantly correlated to the Svalbard record (multi-specimen record: 1895–2010, $R = 0.6$ [N11, $p < 0.05$]; Fig. 3G).

The interpretation of trends in 20th-century sea-ice variability is complicated by underlying low-frequency variability on decadal to multidecadal time scales, which is only partly covered by observational records. Spectral analysis reveals dominant long-term decadal- to multidecadal-scale variability in the algal proxy record (detailed methods of analysis are provided in the Data Repository and Fig. DR1 therein). The 200 yr single-specimen algal proxy record shows low-frequency variability with dominant frequencies at 38 and 91 yr. The combined 120 yr multi-specimen record displays a low-frequency signal with dominant frequencies at 38.5 and 50 yr and a high-frequency signal at 4.1 and 2.7 yr. Multidecadal variability in the Svalbard algal record is similar to the variability displayed in the Newfoundland sea-ice extent index (87–91 yr) and in the algal-based sea-ice reconstruction from Labrador (45–83 yr), which was linked to the Atlantic Multidecadal Oscillation (AMO) (Moore et al., 2017). Persistent multidecadal (~60–90 yr) fluctuations have also been found in multicentury historical Atlantic Arctic sea-ice records, covarying with the AMO (Miles et al., 2014), including the historical sea-ice edge data set (60–80 yr; Divine and Dick, 2006). Similar multidecadal-scale variability, superimposed on the long-term anthropogenic warming trend, is found in many Arctic proxy and climate records and thus needs to be considered in future projections of Arctic sea-ice evolution.

The new algal proxy record provides the first marine annual-resolution long-term sea-ice data from the High Arctic suggesting that sea-ice decline at Svalbard had already started in the early 20th century. The onset of the ongoing sea-ice decline at the end of the Little Ice Age has previously been related to atmospheric warming driven by enhanced atmospheric and ocean heat transport from the North Atlantic to the Arctic, and is believed to be at least partly explained by natural climate-system variability (Bengtsson et al., 2004).

Our data indicate that the lowest sea-ice values during the past 200 yr are from the 1980s to the early 2000s. In addition, the new algal proxy now provides a means to resolve underlying decadal- to multidecadal-scale variability, showing prominent variability at 38–50 and 90 yr, which is not possible with short remotely sensed time series, and for the first time allows tracking of northern Svalbard sea-ice variability back to the start of the 19th century. Although our proxy record provides evidence for brief periods of higher sea-ice cover during the past two centuries as part of low-frequency variations, the long-term declining trend in sea ice around Svalbard started earlier than was previously reported, and is expected to continue with rapid future Arctic warming.


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