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APPENDIX - DATA AND METHODS

Sample collection

Long-lived *C. compactum* coralline algae were collected off northern Spitsbergen during MARIA S. MERIAN cruise MSM55 in June 2016 at the study site "Mosselbukta" (at station MSM55/444 (Wisshak et al., 2017), Ellingsenodden, 79.9°N, 15.9°E; Fig. 1A). The site is influenced by seasonal sea ice cover for 6 months per year on average (based on sea ice maps; details see below at "Instrumental data"). Collection of coralline algal buildups took place by removing them from rocky substrate using a chisel and the manipulator arm of the submersible JAGO. All specimens were collected live from hard substrate at a water depth of 15 m. Appropriate algal specimens for sclerochronological and geochemical analysis were selected according to size (taller specimens = longer record) and smoothness of surface (smoother surface = better developed internal growth increments and lower degree of bioerosion – based on previous experience). Three specimens of the crustose coralline alga *C. compactum* were used in this study. Arctic occurrences of the species *C. compactum* have been described from the Greenland coast (Jørgensbye and Halfar, 2016), the Canadian Arctic Archipelago and northern Labrador (Halfar et al., 2013), Novaya Zemlya (Adey et al., 2015), and Svalbard (this study).

Sample preparation

Untreated coralline algal specimens were slabbed vertically to a thickness of ~1 cm using a rock saw, then thick sections (2 mm) were cut from the slabs. In preparation for microscopic scanning, sample surfaces were polished using diamond-polishing suspensions with grit sizes of 9, 3, and 1 µm on a Struers Labopol polishing disk. High-resolution digital images of the polished surface were produced using an Olympus reflected light microscope (VS-BX) attached to an automated sampling stage and imaging system equipped with the software geo.TS (Olympus Soft Imaging Systems). This setup allows two-dimensional mapping of the surfaces of polished specimens at various magnifications. The resultant high-resolution photomosaics (Fig. 1B) enable the identification and lateral mapping of growth-increment patterns over the entire sample. In preparation for Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) analysis, paths for laser line transects as well as two reference points per sample were digitized on high-resolution photomosaics perpendicular to the direction of growth using geo.TS software. Coordinates of digitized paths and reference points were subsequently transferred to the LA-ICP-MS system. After recoordination of the sample, laser line transects could be precisely positioned along previously digitized paths.

Geochemical sample analysis by LA-ICP-MS

LA-ICP-MS analyses were carried out in the Magmatic and Ore-Forming Processes Research Laboratory at the University of Toronto, Canada. ^{43}Ca and ^{24}Mg contents were measured using a NWR 193 UC laser ablation system coupled to an Agilent 7900 Quadrupole mass spectrometer. Each sample underwent a pre-ablation step to remove surface contaminants and the transects were placed to avoid conceptacles. Measurements were carried out with laser energy densities of 6 J/cm^2, laser pulse rate of 10 Hz and helium as carrier gas.

The rectangular laser slot size was 70 x 10 µm with the long axis oriented parallel to growth increments. Individual line transects measuring up to 6000 µm in length were analyzed with a scan speed of 5 µm/second. ICP-MS cycling time was set so that ~6.5 samples were measured per second resulting in a sampling resolution of 0.775 µm. Several laser transects were run in parallel on the samples allowing the determination of sample heterogeneity and to confirm data reproducibility (Fig. 1B). ^{43}Ca was used as the internal standard with calcium concentrations measured by ICP-OES (Hetzinger et al., 2009). NIST SRM 610 glass (US National Institute of Standard and Technology Standard Reference Material) was analyzed as an external standard twice for 60 s every hour to allow correcting for instrumental drift. An in-house spreadsheet adapted for the line transect data input was used for data reduction.

Development of Chronologies

Chronologies were generated by counting annual growth increments on the mapped and digitized image of the specimens. All samples were live collected, hence the top layer was assigned the year of collection. The yearly growth layers are strongly delineated by bands of short, heavily-calcified cells that are formed during the late autumn and winter, when the reproductive sporangia (conceptacles) are produced (Adey et al., 2013). Yearly growth banding is usually well-defined, although it can be disrupted by invertebrate grazing or boring and other surface damage. High Mg values within the skeleton of *Clathromorphum* are interpreted to correspond to summer periods of growth. Age models were established on the basis of the pronounced seasonal cycle in algal Mg/Ca. Maximum (minimum) Mg/Ca values were tied to August (February) for Mosselbukta samples, which is on average the warmest (coolest) month at the study site. The algal Mg/Ca time series were linearly interpolated between these anchor points using the AnalySeries software (Paillard et al., 1996) to obtain an equidistant proxy time series with a resolution of 12 samples/year. The developed chronologies were refined and cross-checked for possible errors in the age model by comparing annual extreme values in the Mg/Ca ratios to mapped growth increment patterns for each individual year of algal growth. Mean annual extension rates for Mosselbukta samples were obtained from Mg/Ca cycles agemodel and are 125 µm (sample Sv1), 149 µm (sample Sv28), and 145 µm (sample Sv90). Sample Sv1 displays the longest record (1813-2014) and was used separately for comparisons (single specimen record). Samples Sv28 and Sv90 cover the past 120 years (1894-2014) and were averaged with sample Sv1 to form the multi-specimen record (1895-2014, three sample specimens). Mean annual extension rates and Mg/Ca ratio records from samples Sv28 and Sv90 are based on two separate measurement transects (left/right) on each sample, which were averaged. Annual extension rates and Mg/Ca ratios of sample Sv1 are based on one transect. Annually averaged Mg/Ca ratio time series were calculated from monthly-resolved time series. The algal sea ice proxy was calculated by combining normalized mean annual algal extension rates and Mg/Ca ratios by averaging for each sample (Table DR1). Then, the multi-specimen record was calculated by averaging the algal sea ice proxy from all three specimens for the common time period (1895-2014). The longest specimen (Sv1, 1813-2015) is additionally compared separately, referred to as the single specimen record.

Spectral analysis of algal proxy record

Examination of the algal proxy time series using MTM (Multi-taper method) and SSA (Singular Spectrum Analysis) spectra (Ghil et al., 2002) reveals dominant long-term decadal-scale variability in the algal record (Figure DR1). Separate analysis of the long 200-year proxy record (single specimen record, 1813-2014) and the combined 120-year record (multi-specimen record, 1894-2014) shows characteristic low-frequency variability in the 200-year long record with dominant frequencies at 91 (99% sign., explaining 40% variance; Figure DR1A) and 38 years (95% sign., explaining 10% variance). While multidecadal frequencies dominate the record, higher frequency variability is also present (2.6 years, 95% sign., explaining 7% variance). The multi-specimen record is characterized by a combined low-frequency signal with dominant frequencies at 38.5 and 50 years (95%, explaining 42.1% variance; Figure DR1B), and a high-frequency signal at 4.1 (99%) and 2.7 years (95%), explaining 22% of variance. However, the 120-year multi-specimen record is not long enough to detect low-frequency variability with periods of 80-90 years, as observed in the longer 200-year record. In summary, spectral analysis reveals that both, the 200-year single specimen record and the shorter multi-specimen record, are dominated by multidecadal-scale variability.

Instrumental data
Sea ice concentrations were extracted from the HadISST1 data set (Rayner et al., 2003), available for northern Svalbard since 1901 with data gaps. HadISST1 is a combination of monthly globally-complete fields of SST and sea ice concentration on a 1 degree latitude-longitude grid from 1870 to date. Remotely-sensed National Snow and Ice Data Center (NSIDC) sea ice concentration are available from 1979 onwards at 25 x 25 km spatial resolution (https://nsidc.org/). NSIDC (HadISST) sea ice concentration is shown as percent area covered by sea ice in the defined region (NSIDC: 12-20°E, 79-80°N; HadISST: 12-20°E, 75-85°N). Historical sea ice edge anomalies are shown for the Greenland Sea, calculated as a seasonal average of April, June, and August observations using data from the Divine and Dick (2006) dataset. The Greenland Sea area used here compiles historical observations from sectors 2-4 (Divine and Dick, 2006), spatially covering the Greenland Sea, Fram Strait and NW-Svalbard regions including the study site. Sea ice edge anomalies are reported as anomalies from mean sea ice edge positions and are based on different historical sources before the mid-20th century, such as ship log books and maps, and reports from whalers and sealers. Data density is irregular and sparse before 1850.

Figure DR1. Spectral analysis of algal time series: Spectral analysis are calculated using Multi-taper method (MTM, left column) and Singular Spectrum Analysis (SSA, right column). (**A**) For the single specimen record (based on specimen Sv1, 1813-2014) multidecadal signals are found at 91 and 38 years (explaining 40% and 10% variance) and an interannual signal at 2.6 years (7% variance). (**B**) For the multi-specimen record (averaged from three samples, 1895-2014) low-frequency multidecadal signals are found with dominant frequencies at 50 and 38.5 years (42% variance), and interannual signals at 4.1 and 2.7 years (38% of variance). Time series were normalized and detrended prior to analysis. Periods (years) of peaks significant at 95 and 99% level are indicated MTM plots (left). The significance estimates in MTM are independent of the spectral power. In SSA plots (right) dominant multidecadal components are reconstructed (blue) and shown alongside the original algal time series (black).

Table DR1. Primary data from Svalbard samples used for calculating the algal sea ice proxy: (A) Mean annual extension rates for Mosselbukta samples were obtained from Mg/Ca cycles agemodel and are displayed in µm/year. For samples Sv28 and Sv90, two transects were measured and averaged, respectively. Annual mean extension rates from each sample were normalized to unit variance by subtracting the mean and dividing by standard deviation (STD). **(B)** Algal Mg/Ca ratio time series in ((µg/g)/(µg/g)). Mg/Ca ratios for sample Sv1 are based on one measurement transect, records from samples Sv28 and Sv90 are based on two separate measurement transects (left/right) on each sample, which were averaged before normalizing data to unit variance by subtracting the mean and dividing by standard deviation (STD). **(C)** Algal sea ice proxy calculated from normalized data shown in (A) and (B). First, the sea ice proxy is calculated by averaging normalized extension rates and Mg/Ca ratios for each sample. Then, the multi-specimen average is calculated from all three samples for the common time period (1895-2014). The single specimen sea ice proxy record is based on the the oldest specimen (Sv1, 1813-2014). All annual mean proxy records were calculated from monthly-resolved algal proxies for three samples: Sv1, Sv28, Sv90.

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