

Suitability of the Coralline Alga *Clathromorphum compactum* as an Arctic Archive for Past Sea ice Cover

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Abstract

Arctic sea ice cover has been steeply declining since the onset of satellite observations in the late 1970s. However, the available annually resolved sea ice data prior to this time are limited. Here, we evaluated the suitability of annual trace element (Mg/Ca) ratios and growth increments from the long-lived annual increment-forming benthic coralline red alga, *Clathromorphum compactum*, as high-resolution sea ice cover c. It has previously been shown that growth and Mg/Ca of *C. compactum* are strongly light controlled and therefore greatly limited during polar night and underneath sea ice cover. We compare algal data from 11 sites collected throughout the Canadian Arctic, Greenland and Svalbard, with satellite sea ice data. Our results suggested that algal growth anomalies most often produced better correlations to sea ice concentration than Mg/Ca alone or when averaging growth and Mg/Ca anomalies. High Arctic regions with persistently higher sea ice concentrations and shorter ice-free seasons showed strongest correlations between algal growth anomalies and satellite sea ice concentration over the study period (1979-2015). At sites where ice breakup took place prior to the return of sufficient solar irradiance, algal growth was most strongly tied to a combination of solar irradiance and other factors such as temperature, suspended sediments, phytoplankton blooms and cloud cover. These data are the only annually resolved in situ marine proxy data known to date and are of utmost important to gain a better understanding of the sea ice system and to project future sea ice conditions.

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Key Points:

- Annual proxy anomalies from growth increments and Mg/Ca ratios in calcareous algae were compared to satellite sea ice concentrations
- Algal growth anomalies most significantly correlated to sea ice concentrations at sites with medium wave exposure and >5 months sea cover
- Downsampled to five-year averages, correlations are strengthened and can capture summer sea ice concentrations better than annual averages

27 Abstract

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29 1970s. However, the available annually resolved sea ice data prior to this time are limited. Here,
30 we evaluated the suitability of annual trace element (Mg/Ca) ratios and growth increments from
31 the long-lived annual increment-forming benthic coralline red alga, *Clathromorphum*
32 *compactum*, as high-resolution sea ice cover proxy. It has previously been shown that growth and
33 Mg/Ca of *C. compactum* are strongly light controlled and therefore greatly limited during polar
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45

46 Plain Language Summary

47 Natural layered structures such as tree rings and mollusk shells' growth layers archive
48 environmental data in their rings or layers as they grow. A lesser known and emerging
49 environmental archive is the coralline red algae species, *Clathromorphum compactum*, that lives
50 on the Arctic and North Atlantic seafloor (10-30m deep). It grows on solid substrate by forming
51 a new calcified layer of growth every year, ultimately building up dome-like crusts over tens or
52 hundreds of years. Different thicknesses and amounts of magnesium in their annual layers
53 depend on ocean temperature and sunlight availability. Because sea ice forms under cold
54 conditions and blocks sunlight from reaching the sea floor, we hypothesized that magnesium
55 chemistry and growth also responded to sea ice conditions. Here, we evaluated the relationship

between algal layer thicknesses and/or magnesium chemistry to sea ice data derived from satellite images at 11 sites. Strong relationships between algal growth and sea ice cover were found at exposed sites with longer seasonal-ice cover duration. Recent reduction of sea ice in certain regions have weakened the growth-sea ice relationship. A deeper understanding of past ice conditions can provide extremely valuable data for climate models to more accurately predict future sea ice scenarios.

1 Introduction

1.1 Sea ice effects on global climate change and lack of long-term high-resolution sea ice records

Summer sea ice extent has declined by 12.9 % per decade since 1979 relative to the 1981-2010 average (Cavalieri & Parkinson, 2012; Comiso, Meier, & Gersten, 2017). This alarming rate of decline has potentially devastating impacts on Arctic ecosystems, and destabilizing effects on ocean circulation, global climate, and human populations due to the connection of sea ice to multiple feedback mechanisms including the ice-albedo feedback (Meier et al., 2014). However, current climate model projections are unable to fully capture annual sea ice variability and often underestimate the amount of sea ice decline due to a limited understanding of the internal and anthropogenic processes driving sea ice loss (Ding et al., 2017). Models that project future climate scenarios utilize multiple past sea ice datasets and sea ice-related variables. The sea ice records with the highest temporal and geographical resolutions are derived from satellite datasets providing almost daily global coverage back to 1979. Sea ice records that extend further back than 1979 are made from aggregated datasets with lower geographic coverages and temporal resolutions. Sources include: stations, fishing, shipping, navy, research vessels, experiments, exploration expeditions, buoys, historical data sources (Polyak et al., 2010; Worley, et al., 2005). However, these datasets are spatially and temporally discontinuous. For instance, historical observations were biased toward the ice margins due to the constraints of penetrating the ice pack. In addition, whale and seal hunting data sources excluded internal ice pack regions since marine life is typically more abundant along ice margins (e.g., Hill & Jones, 1990; Mahoney et al., 2011; Walsh et al., 2017).

1.2 Paleo-sea ice proxies: strengths and limitations

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87 Proxy information can yield sea ice information from less accessible internal sea ice regions and
 88 further back in time. Terrestrial sea ice proxies such as ice cores from ice sheets, tree-ring
 89 records, and lake sediments can provide information on thermal conditions affecting sea ice
 90 formation and melt (e.g., Kinnard et al., 2011) but are remote from sea ice regions and may only
 91 yield limited information on the dynamics of sea ice. Meanwhile, marine proxies from sediment
 92 cores provide better information on sea ice dynamics that can extend back millennia. The highly
 93 branched isoprenoid biomarker with 25 carbon atoms (IP25) found in ocean sediments can
 94 establish the presence or absence of seasonal sea ice as it is originally formed in first-year ice
 95 and brine channels (Belt et al., 2007), while the quantitative open-water phytoplankton-IP25
 96 index (PIP25) can further quantify the concentration of sea ice cover and changes in distribution
 97 (Belt, 2019; Köseoğlu, et al., 2018; Müller et al., 2011; Stein & Fahl, 2013). However, regional
 98 sedimentation rates are a limiting factor for proxies based on ocean sediment cores, yielding sub-
 99 decadal resolution data only in the best situations with interpolated two- to five-year resolutions
 100 (Backman, et al., 2004; Belt et al., 2012; Ran, et al., , 2011; Sicre, Jacob, et al., 2008; Sicre,
 101 Yiou, et al., 2008). Further, the use of assemblage analyses based on the identification and
 102 quantification of diatoms, foraminifera, ostracods and dinoflagellate cysts (i.e., dinocysts) can
 103 also be challenging due to their presence in both perennial and seasonal sea ice cover
 104 environments (Gemery et al., 2017; Kucera et al., 2005; Seidenkrantz, 2013). Since all sea ice
 105 proxies are geographically and temporally limited, a network of proxy records is needed to
 106 capture the full extent of spatial and temporal variability of sea ice dynamics and
 107 thermodynamics in the Arctic (Kaufman, 2009). Accordingly, high-resolution proxies that
 108 provide annual or seasonal sea ice information for the past millennia are necessary to calibrate
 109 climate models that project future sea ice behavior.

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111 1.3 The coralline red alga sea ice proxy

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113 An emerging archive for Arctic sea ice conditions is the coralline red algae species
 114 *Clathromorphum compactum* (Halfar et al., 2013; Hetzinger, et al., 2019), a calcifying alga that
 115 grows ubiquitously in near-shore arctic and subarctic environments including the North Atlantic
 116 and the Bering Sea where rock and boulders cover the shallow benthic seafloor (Adey, 1965;

117 Adey, Halfar, & Williams, 2013). *C. compactum* produce tree-ring-like annual growth
118 increments in their calcified (CaCO_3) skeletons that are high in magnesium (Adey et al., 2013)
119 (Figure 1). These slow growing and long-lived algae can grow upwards of 600 years (Halfar et
120 al., 2013). As they grow, they deposit layers of calcified cells in varying sizes and cell wall
121 thicknesses that result in increments of lighter and darker bands (Foster, 2001). Experimental
122 tank studies of *Clathromorphum* sp. have shown that their growth is highly dependent on both
123 sunlight and temperature (Adey, 1970; Williams et al., 2018). Additionally, the variability of
124 magnesium to calcium ratios (Mg/Ca) found in *C. compactum*'s annual growth layers is cyclical
125 and strongly correlates with seasonal changes in surrounding sunlight availability and
126 temperature (Williams et al., 2018). *C. compactum* produces its normal range of tissues with
127 similarly complex high-magnesium calcitic wall structures both in the light and in the dark.
128 However, growth is dependent upon the production and storage of photosynthate. Growth and
129 calcification can occur for at least two months in the dark, at which point it ceases, following the
130 exhaustion of stored photosynthate (Williams et al., 2018). The crust can exist for long periods
131 without light, growth or photosynthesis, and growth will resume with the return of new light for
132 photosynthesis. Furthermore, growth rates have been shown to vary according to latitude and
133 regional sunlight access (Halfar et al., 2013). Accordingly, growth rates are higher in coastal
134 Maine (43°N) (400 $\mu\text{m}/\text{yr}$), as compared to southern Labrador (52°N) (240 $\mu\text{m}/\text{yr}$), and the
135 Canadian Arctic Archipelago (73°N) (61 $\mu\text{m}/\text{yr}$) (Halfar et al., 2013). As growth and Mg/Ca
136 ratios of *C. compactum* have been shown to be stimulated through photosynthesis, blocking of
137 sunlight by seasonal sea ice cover has been hypothesized to reduce the widths of annual growth
138 increments and reduce annual Mg/Ca ratios.

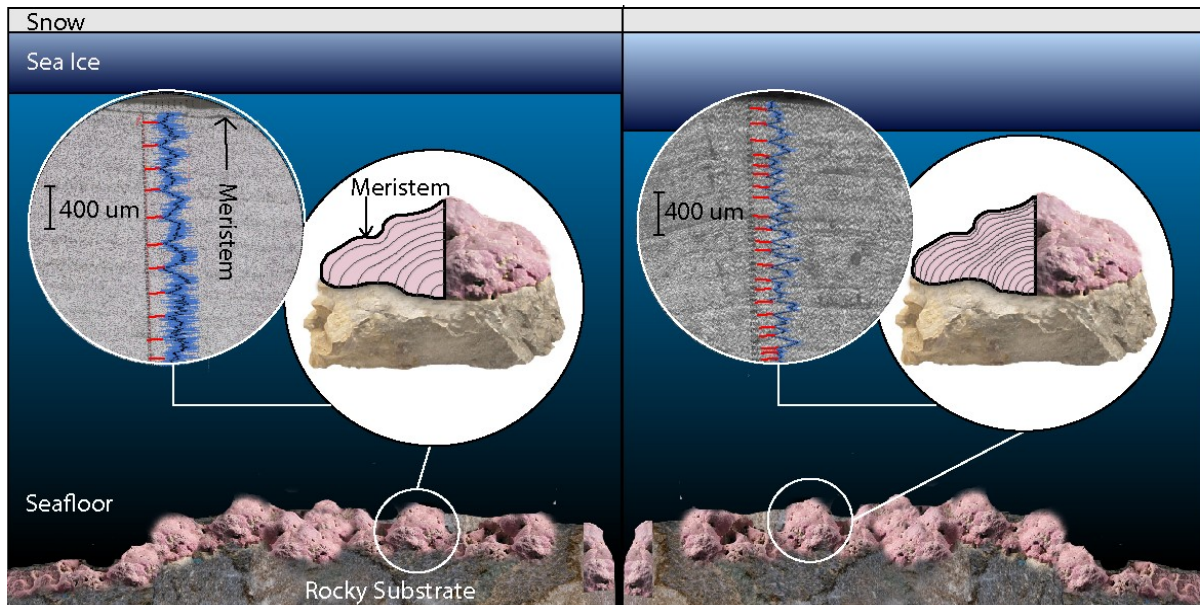


Figure 1. Schematic representation of relationship between length of sea ice cover and *C. compactum* growth and Mg/Ca ratios. Left panel indicates shorter duration of thin sea ice cover and thicker growth increments in depicted cross-section. Right panel indicates longer period of thick sea ice cover and consequently thinner algal growth increments. Mg/Ca ratios, superimposed on high-resolution image of internal growth increments, are cyclical on annual timescales and match annual growth rates. Annual Mg/Ca minima are indicated with red lines and line-up with darker slow growth (winter) CaCO_3 layers. The meristem, typically, lying 5-10 cells below the algal surface is where algal growth and calcification occur. The overlying epithallus, weakly calcified and often grazed by molluscs, is ephemeral and location of most photosynthesis. Calcified tissue underlying meristem, the perithallus, builds up annual increments that provide multiannual proxy data.

It has previously been shown that a combination of normalized growth rates and Mg/Ca ratios (i.e., algal anomalies) significantly inversely correlated with satellite-derived sea ice concentrations near algal collection sites in Arctic Bay (Nunavut) and the Kingitok Islands (Labrador) in Canada (Halfar et al., 2013). This suggested that when there was a longer duration of higher sea ice concentrations, less light reached the seafloor during the year, producing less growth (thinner increments) and reduced Mg incorporation (lower Mg/Ca ratios). Furthermore, a recent proxy time series of *C. compactum* from Svalbard, Norway, showed significant

correlations between algal anomalies and regional sea ice concentration data and other Arctic sea ice proxy reconstructions, which demonstrated a reduction of sea ice and a general warming trend in Svalbard over the 20st century (Hetzinger et al., 2019).

In order to assess the robustness of sea ice proxies, fundamental questions regarding their strengths and weaknesses and the geographic and temporal contexts in which each proxy can be applied must be answered (De Vernal, et al., 2013). While, the above-mentioned studies have established the potential for *C. compactum* to be used for sea ice reconstruction, the strengths and weaknesses of the algal anomaly sea ice proxy have not been assessed in a multi-site comparison across the Arctic landscape. Furthermore, while the combination of Mg/Ca ratios and growth increment data has been correlated to sea ice concentration, it has not been established if both equally show a relationship or if one anomaly alone could be used exclusively to compare to sea ice conditions. In this study, we investigate 30 *C. compactum* samples across 11 sites encompassing Svalbard (Norway), Western Greenland, Eastern Labrador (Canada), and multiple locations in Nunavut (Canada) (Figure 2). Their individual relationships to regional sea ice conditions were evaluated by determining the degree of correlation to satellite-derived sea ice concentration datasets, ice charts and satellite images.

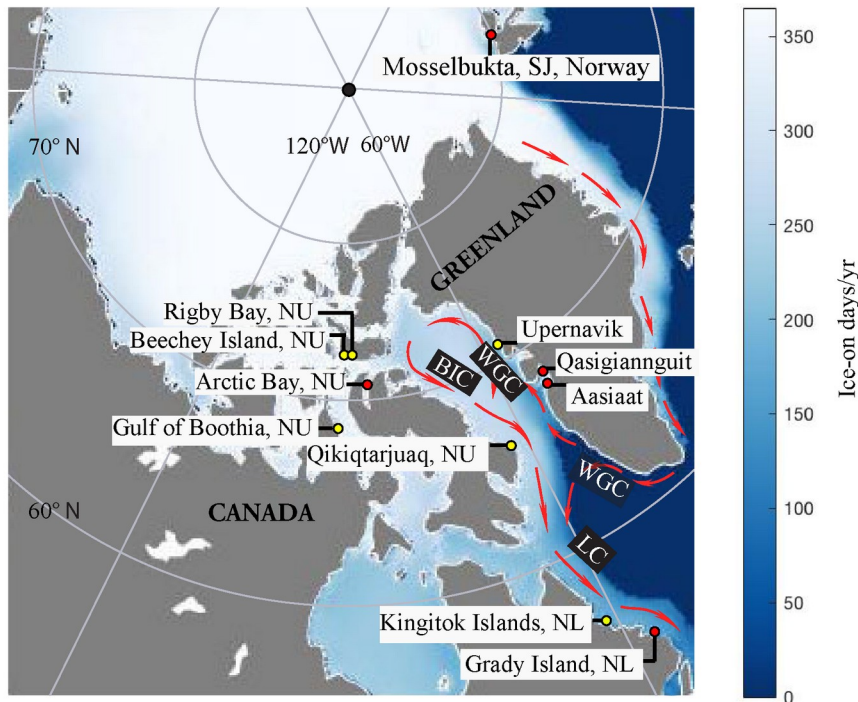


Figure 2. Studied arctic and subarctic *C. compactum* collection sites in Nunavut (NU) and Labrador (NL) in Canada, Greenland, and Svalbard (SJ) in Norway. Yellow dots indicate sites with significant relationships between summer sea ice concentration (SIC_{SUMMER}) and algal growth while red dots indicate sites with insignificant relationships that also tend to have shorter durations of ice cover near the ice margin. Average number of ice-on days with >15% ice cover over study period (1979-2015) shown graded from white (365 days) to dark blue (0 days). Currents depicted in black boxes: West Greenlandic Current (WGC); Labrador Current (LC) and; Baffin Island Current (BIC). Data source: daily NSIDC sea ice concentration dataset 25-km resolution.

2 Materials and Methods

2.1 Sample collection and preparation

Live specimens of *Clathromorphum compactum* were collected in 2008, 2010, 2011, 2014, and 2016, via SCUBA from 10-20 m depth (Figure 2, Table 1). Samples were cut along the axis of growth to expose growth layers with an Isomet precision saw. Samples were then polished with 9 µm, 3 µm, and 1 µm diamond-polishing suspension solutions on a Struers Labopol polishing disk and placed in an ultrasonic bath between polishing steps to remove adhering media. Sample cross-sections were imaged with an Olympus VS-BX reflected light microscope and automated stage using Geo.TS software (Olympus Soft Imaging Systems) that generated photomosaics of imaged area. From these images, the samples providing the longest records, regular growth, and presenting the least disruptions (e.g., cracks, disrupted growth, or conceptacles – reproductive structures of the alga) were selected for geochemical analysis. Samples were also inspected to ensure a visible meristem and epithallus – the growing edge and protective layer of the organism exposed to light – to confirm the deposition date of the first calcified perithallial layer beneath (i.e. at time of collection) (Figure 1).

2.2 Analytical protocols for Mg/Ca and growth increment measurements

Specimens from Svalbard, Greenland, Rigby Bay, Beechey Island and the Gulf of Boothia collected in 2016 had laser ablation paths digitized on Geo.TS and path coordinates transferred

to a NWR 193 UC laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) system coupled with an Agilent 7900 quadrupole mass spectrometer at the University of Toronto's Earth Science Centre. Measurements of Mg/Ca were obtained by conducting continuous laser ablation line scans at 5 $\mu\text{m}/\text{sec}$ speed, an aperture size of 10 x 70 μm and 10 Hz pulse rate. Samples from Arctic Bay, Kingitok Islands and Qikiqtarjuaq, collected in 2008, 2011, and 2014 respectively, were analysed for Mg/Ca using a JEOL JXA 8900 RL electron microprobe at the University of Göttingen with acceleration voltage of 10kV, beam current of 12nA and spot diameter of 3.5 μm with a spacing of 10 μm between measurements along the axis of growth (for details of method see Halfar et al., 2013). Samples collected from Grady Island in 2010 were analysed at the University of Mainz, Germany in the Earth System Science Research Centre using an Agilent 7500 quadrupole-ICP-MS attached to a New Wave Research UP-213 laser ablation system. Ablation measurements were obtained with a 65 μm spot size along continuous transects, a 10 $\mu\text{m}/\text{sec}$ speed, 10 Hz pulse rate, laser energy density of 6 J/cm², and helium carrier gas. All elemental data were calibrated with NIST SRM 610 standard (see details in Hetzinger et al., 2011). Resulting Mg/Ca data for all analyzed specimens was down-sampled to 12 measurements/year resolution with AnalySeries software (Paillard et al., 1996). When two measurement transects were taken from a sample, annual growth increment widths and Mg/Ca ratios were averaged between transects and were compared to aid in the construction of age models. Growth increment widths were calculated by measuring the distance between the time-stamped laser ablation measurements or electron microprobe spot measurements of two sequential Mg/Ca minima representing the space of one year (red lines, Figure 1). Both growth increment and Mg/Ca measurements were normalized into unitless anomalies. Annual growth increment and Mg/Ca anomalies were evaluated separately and also averaged to produce combined algal proxy anomalies.

2.3 Satellite datasets and spatial correlations

Combined algal anomalies were regressed against monthly and annually averaged sea ice concentrations (SIC) from the gridded National Snow & Ice Data Centre (NSIDC) Sea ice Concentration Dataset (Version 3) that extend from 1979 to present (<https://nsidc.org/data/g02202>; Peng et al., 2013). These data were obtained through passive

microwave sensors Nimbus-7 SMMR and DMSP SSM/I-SSMIS that measure surface brightness converted to 25 x 25 km gridded sea ice concentrations via algorithms that also reduce the bias between different instruments used during the satellite era (Meier et al., 2017; Peng, et al., 2013). Due to some sites being incorporated in gridded cells classified as land, SICs from the cells surrounding all collection sites were averaged when calculating correlations between regional sea ice conditions (75-km resolution) and algal anomalies. Data gaps were found in December 1987 to January 1988 and were therefore not used in the calculation of annual SIC averages. Daily NSIDC SIC 25-km resolution dataset was used to determine the average number of ice-free days (<15%) per year for the 75-km gridded area around each of the collection sites. SIC monthly means that significantly inversely correlated with algal anomalies ($p < 0.05$) were pooled together by averaging these months' SIC, which were then statistically regressed against algal anomalies. Regional maps displaying spatial regression analyses of algal anomalies and sea ice concentrations were generated with MATLAB version R2018a and *m_map* add-on. Sea surface temperatures from HadISST dataset at a 1° resolution (Rayner et al., 2003) were also used to conduct regression statistics between algal anomalies and nearest 1° grid cell values (<https://www.metoffice.gov.uk/hadobs/hadisst/>). The Norwegian Meteorological Institute's archived nearly daily sea ice charts (1997-2015) for the Fram Strait and Svalbard regions (<https://cryo.met.no/archive/ice-service/icecharts/quicklooks/>) and satellite imagery from NASA Worldview (<https://worldview.earthdata.nasa.gov>) were used to examine sea ice concentrations at a higher spatial resolution than the NSIDC dataset. Satellite cloud fraction cover data (EUMETSAT/CMSAF; 0.25° resolution) obtained from KNMI Climate Explorer ([climexp.knmi.nl/select.cgi?cfc_cmsaf](http://climexp.knmi.nl/select.cgi?cfc_cmsaf;); http://dx.doi.org/10.5676/EUM_SAF_CM/CLARA_AVHRR/V002), and monthly chlorophyll α concentrations (MOSISA_L3mCHL v2018; 4-km resolution) were obtained through NASA Earth Data's tool Giovanni (<https://giovanni.gsfc.nasa.gov>; <https://doi.org/10.5067/AQUA/MODIS/L3M/CHL/2018>). Linear regression tests were run between algal anomalies and monthly or annual SIC averages and durations of ice-free season for all sites (75-km resolution). Multiple months' SICs were averaged when algal anomalies correlated with more than one monthly SIC (SIC_M), which were restricted to the highest solar irradiance season of May to October (Adey et al., 2013). SIC_M means were then regressed against algal anomalies.

272 **Table 1.** Sample information for this study and time period compared to satellite records
273

Site	Latitude/ Longitude	Sample ID	Measurement transects/sample	Period analyzed
Svalbard, Norway				
Mosselbukta	79°55'37.0"N 15°54'07.9"E	Sv1	2	1979-2014↓
		Sv18	1	1979-2015
		Sv28	2	1979-2015
		Sv47	1	1979-2015
		Sv90	2	1979-2015
West Greenland				
Aasiaat	68°44'9.83"N	2016_1_19	2	1979-2015
	52°32'10.86"W	2016_1_46	2	1979-2015
Qasigianniguit	68°53'51.54"N	2016_4_2	2	1979-2015
	51°16'54.19"W	2016_4_29	2	1988-2015
Upernavik	72°23'2.94"N	2016_7_21	2	1979-2015
	55°31'50.77"W	2016_7_27	2	1979-2015
		2016_7_30	2	1979-2015
East Labrador, Canada				
Grady Island	53°47'60.00"N	10-18_18-20	2	1979-2008↓
	56°24'30.00"W	10-18_15-17	2	1978-2008↓
Kingitok Islands	55°23'53.88"N	Ki1	1	1979-2010
	59°50'48.12"W	Ki2	1	1979-2010
Nunavut, Canada				
Qikiqtarjuaq	67°2'17.52"N	2014_4_1	2	1979-2012↓
	62°14'56.76"W	2014_4_2	2	1980-2012↓
		2014_4_3	2	1979-2012↓
Gulf of Boothia	70°24'18.12"N	16_49_80	2	1979-2015
	91°50'39.3"W	16_49_131	2	1979-2015
Arctic Bay	73° 1'2.64"N	AB1	1	1979-2007
	85° 9'12.96"W	AB30	1	1979-2007
		AB31	2	1979-2007
Rigby Bay	74°33'37.50"N	16_22_11	2	1979-2015
	90° 1'54.48"W	16_22_39	2	1979-2015
		16_22_90	2	1979-2015
Beechey Island	74°42'54.46"N	16_24_2b	2	1979-2015
	91°47'29.35"W	16_24_15	2	1979-2015
		16_24_41b	2	1979-2015

274 Note. Downward arrows indicate that a one-year lag was identified in the time-series.

3 Results

3.1 Annual mean Mg/Ca and growth increment comparison

Based on our hypothesis, algal growth and Mg/Ca anomalies were expected to demonstrate a negative correlation to annual (SIC_A), monthly (SIC_M) or summer (SIC_{SUMMER}) SIC, and a positive correlation to the duration of the ice-free period. Mg/Ca ratios and growth increments were regressed independently against annual sea ice concentrations (SIC_A) to determine whether they equally contributed to correlations between SIC_A and the combined algal anomalies. The results revealed that both growth increments and combined algal anomalies had the strongest significant negative correlations with SIC_A at four sites (Figure 3). However, growth increment anomalies alone outperformed the other proxies by producing significant negative correlations with SIC_A at seven sites compared to five and four for combined algal anomalies and isolated Mg/Ca anomalies, respectively (Figure 3). Since the results suggest a more robust relationship between growth increments and SIC_A at most sites, the rest of the results and discussion will focus only on the growth increment anomaly results.

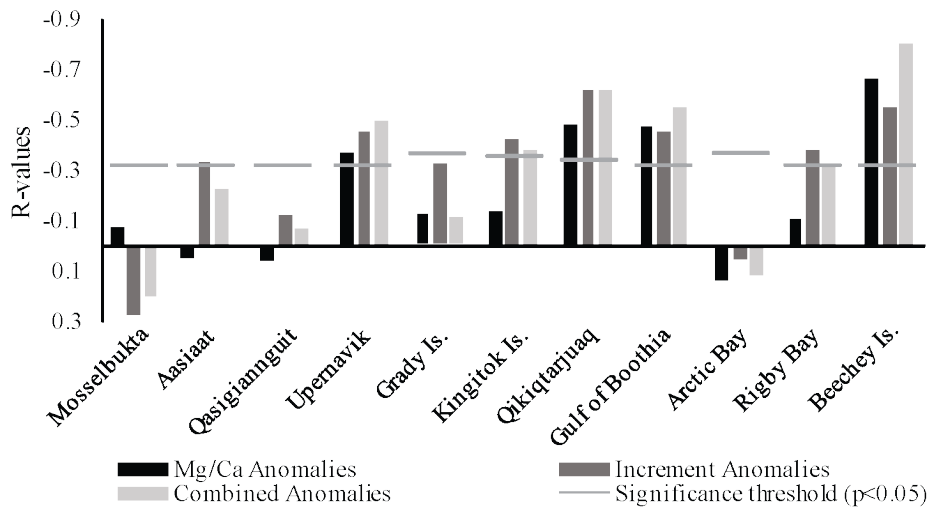


Figure 3. Mg/Ca, growth increment, and combined algal anomalies regressed against SIC_A (1979-sample collection date). Horizontal lines indicate threshold for significance ($p < 0.05$).

3.2 Relationship between sea ice and algal growth anomalies

Regression results showed that algal growth anomalies at 7 out of 11 sites had significant negative correlations with SIC_A ($p < 0.05$), 2 of which tested as significantly positive correlations with the annual durations of the ice-free period (i.e., days with $< 15\%$ SIC; Table 2). Algal anomalies from 8 sites significantly inversely correlated with at least one month of the monthly resolved NSIDC dataset (SIC_M) during the study period (Table 2). Among these, Aasiaat showed a negative correlation to May only, when sea ice typically breaks up in this location. While the annual SIC averages were used for comparison (SIC_A), previous studies suggested that growth resumes after a winter shutdown, once solar irradiance reaches the seafloor when sea ice breaks up (Adey et al., 2013). Accordingly, summer month SIC averages (May-October) were isolated from the annual dataset and compared to growth anomalies. Six sites had growth anomalies that significantly correlated with SIC_{SUMMER} . Growth anomalies with non-significant correlations or low significance to regional SIC tended to be from sites closer to the ice margin with longer ice-free periods (red dots; Figure 2). In comparison to annual means, regression results of five-year running means were more significant (i.e., lower p-values), especially in regions with shorter ice-free periods, at the majority of sites (N5; Table 2). Algal growth anomaly time series from individual sites further show the synchrony with SIC_{SUMMER} at most sites (Figure 4).

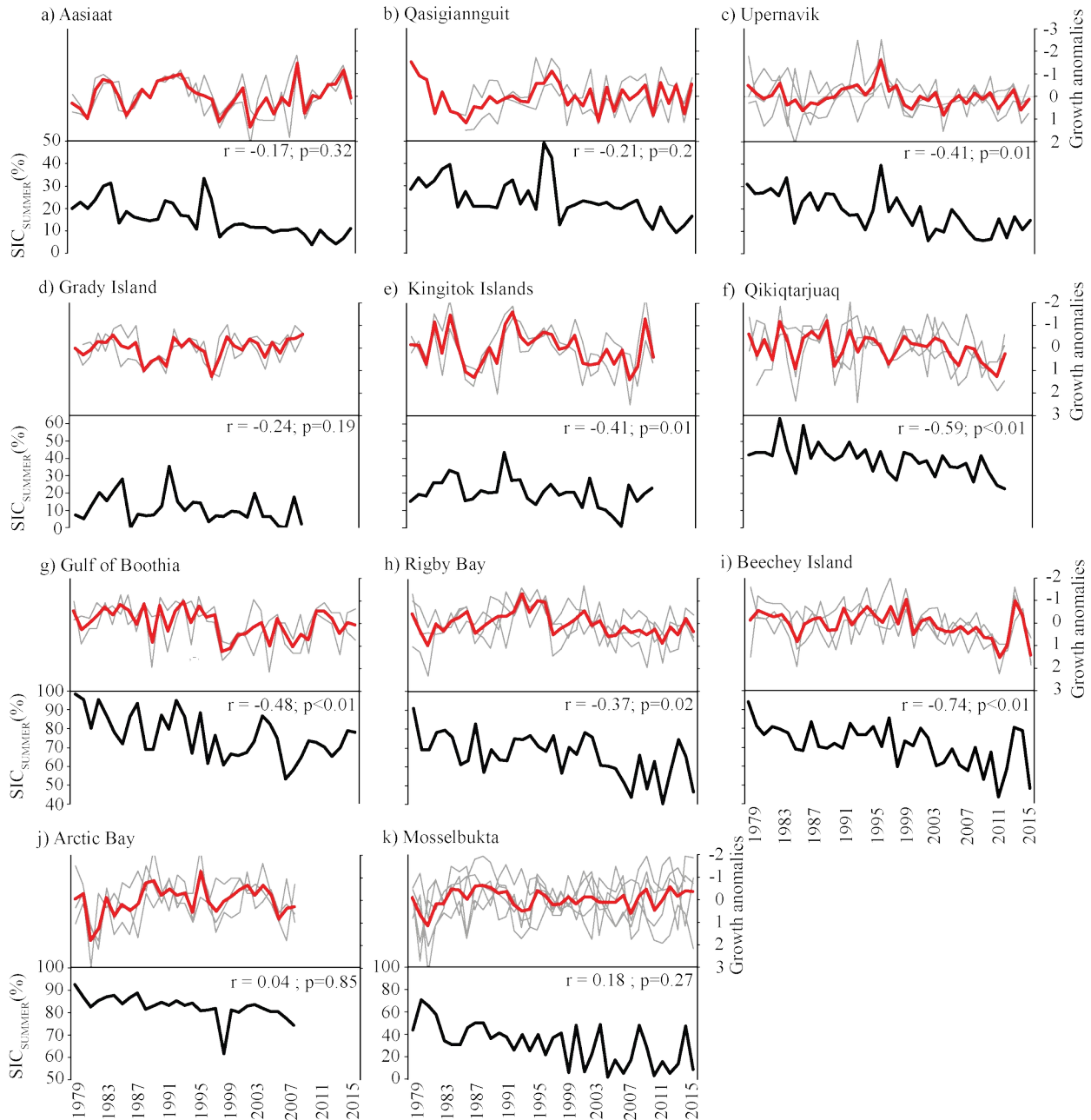


Figure 4. Algal growth anomalies (red) and SIC_{SUMMER} (black: May-Oct means) time series. Algal growth anomalies from individual samples in grey. Note that algal growth anomalies are presented on inverted axis.

Table 2
Results of regression analysis between growth increment anomalies and sea ice conditions (R- and p-values)

Site	Mean SIC _A	Mean Ice-free days	Correlations with growth increment anomalies															
			SIC _A (Jan-Dec)				SIC _M						SIC _{SUMMER} (May-Oct)				Ice-free days	
			R	p	R _(N5)	p _(N5)	Months (p<0.05)	R	p	SIC _{M(N5)} (p<0.05)	R _(N5)	p _(N5)	R	p	R _(N5)	p _(N5)	R	p
Mosselbukta, NO	39%	217	0.27	0.1	0.01	0.95	**	**	**	**	**	**	0.18	0.27	-0.05	0.80	-0.004	0.98
Aasiaat, GL	36%	204	-0.34	0.04	-0.44	0.01	May	-0.40	0.02	May	-0.58	0.0004	-0.17	0.32	-0.23	0.19	0.14	0.41
Qasigiannguut, GL	45%	229	-0.13	0.46	0.03	0.86	Aug-Oct	-0.39	0.02	Aug-Oct	-0.68	0.00001	-0.21	0.20	0.06	0.76	0.001	0.99
Upernavik, GL	46%	218	-0.46	0.005	-0.49	0.004	Jun; Aug-Oct;	-0.45	0.005	May; Aug-Oct	-0.50	0.003	-0.41	0.01	-0.51	0.002	0.12	0.45
Grady Island, NL	38%	287	-0.30	0.10	-0.01	0.95	**	**	**	**	**	**	-0.24	0.19	-0.20	0.32	-0.11	0.56
Kingitok Islands, NL	44%	201	-0.42	0.015	-0.59	0.001	Jun-Jul	-0.44	0.01	May-Jul	-0.66	0.0001	-0.44	0.01	-0.66	0.0001	0.27	0.14
Qikiqtarjuaq, NU	67%	120	-0.54	0.001	-0.73	4.9E-06	Jul-Sep;	-0.66	2.1E-05	Jun-Aug; Oct	-0.81	4.4E-08	-0.59	0.0002	-0.78	3.5E-07	0.43	0.01
Gulf of Boothia, NU	88%	112	-0.46	0.004	-0.79	5.7E-08	Jun-Oct	-0.48	0.003	May-Oct	-0.78	5.4E-07	-0.48	0.003	-0.78	5.4E-07	0.33	0.04
Arctic Bay, NU	90%	190	0.06	0.77	0.47	0.02	**	**	**	**	**	**	0.04	0.85	0.37	0.07	-0.01	0.95
Rigby Bay, NU	82%	132	-0.38	0.02	-0.65	0.00004	Aug-Oct	-0.39	0.02	May-Jun; Aug-Oct	-0.70	4.7E-06	-0.37	0.02	-0.65	3.8E-05	-0.31	0.07
Beechey Island, NU	85%	130	-0.55	0.0004	-0.59	0.0003	May-Oct	-0.74	1.6E-07	May-Oct	-0.90	6.9E-13	-0.74	1.6E-07	-0.90	6.9E-13	-0.31	0.07

Note. Months falling between May and October that individually produced significant and negative correlations to algal growth anomalies are labelled under SIC_M: Months (p<0.05). Monthly SIC that significantly inversely correlated to algal growth anomalies when downsampled to five-year running means are labelled under SIC_{M(N5)} (p<0.05). All mean values calculated for 1979 to year of collection. Significant correlations (p<0.05) shaded orange. Five-year running mean comparison indicated by N5 subscript. Sites with no significant correlating months indicated with two asterisks (**). Positive correlation to SIC and negative correlations to mean ice-free days shaded in grey.

3.3 Spatial patterns of sea ice correlation

Figure 5 illustrates that most sites had inverse relationships with regional SIC_{SUMMER}. Algal growth anomalies from sites with the most significant negative correlations with SIC_{SUMMER} tended to exhibit a strong regional relationship with large Arctic areas. For example, Beechey Island had the strongest negative correlations around the collection site, but also had strong correlations with most of the Canadian Arctic Archipelago, likely owing to similar regional sea ice dynamics (Melling, 2002). On the Labrador coast, regional correlations around Kingitok Islands and Grady Island were influenced by the Labrador Current with negative correlations extending to the west coast of Greenland. The Baffin Island current seemed to be mostly affecting the algal-sea ice relationship at Qikiqtarjuaq, while the West Greenlandic current seemed to have most of an effect on Upernavik algal anomalies.

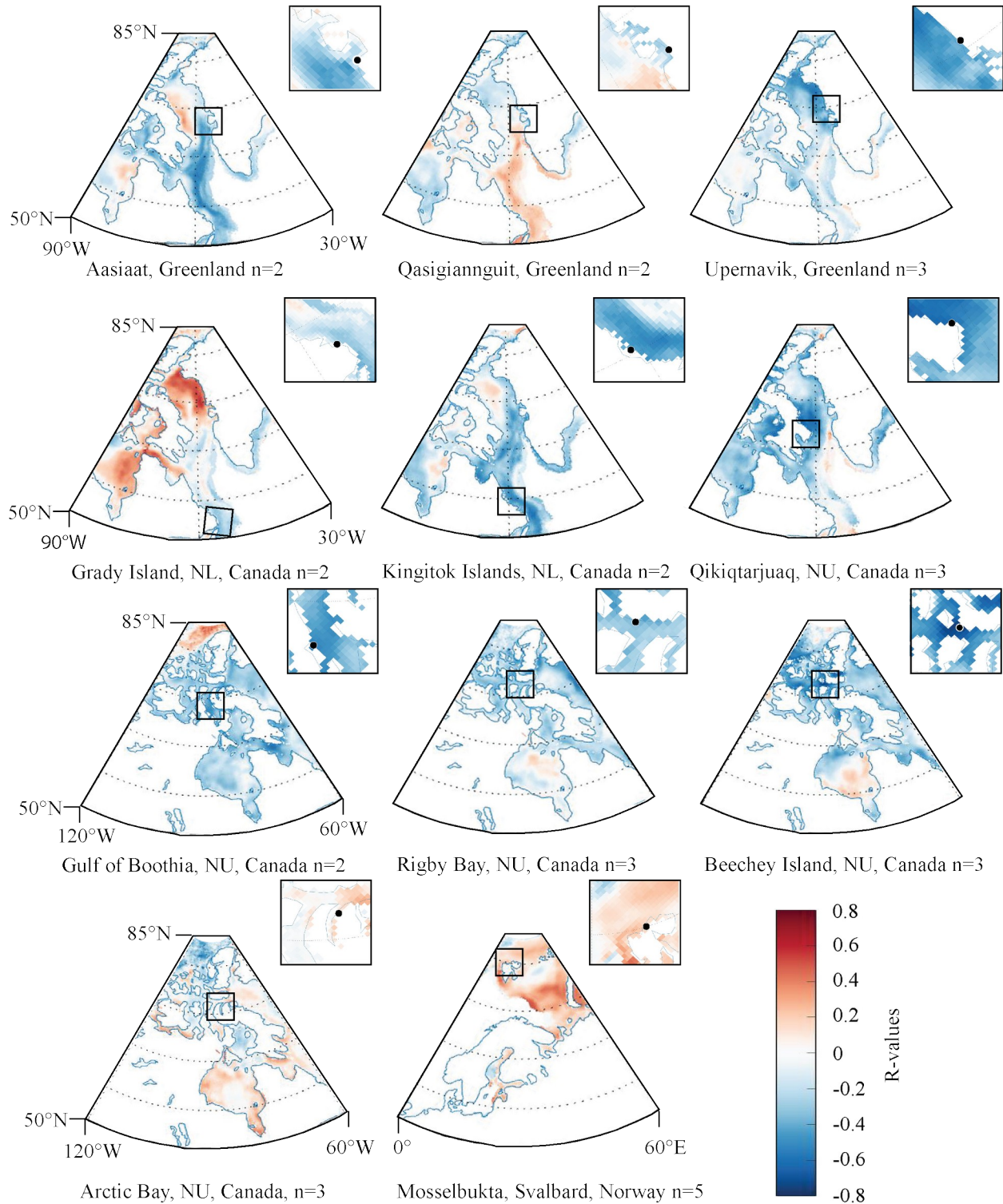


Figure 5. Spatial correlations between SIC_{SUMMER} and algal growth anomalies. SIC data retrieved from NSIDC Sea ice Concentration Version 3, monthly datasets. Spatial correlations calculated with Matlab mapping toolbox. Black dots in inset images indicate collection sites. Time series length varied depending on algal collection date: see Table 1.

3.4 Algal growth-temperature relationship

According to experimental results, *C. compactum* was expected to exhibit higher growth in warmer SST conditions, therefore algal growth anomalies should positively correlate to SST to demonstrate the growth temperature dependence (Williams et al., 2018). Correlations of algal growth anomalies with SST_A and SIC_A were not significantly different (paired two-tailed t-test: df=10, t=-2.09, p=0.06, CV=2.23) owing to the thermal relationship between sea ice and SST at an annual resolution. SST_{SUMMER} correlated to algal growth anomalies at four sites, nearly half of the sites that SIC_{SUMMER} significantly correlated to. SST_{SUMMER} also produced weaker relationships to algal growth than did SIC_{SUMMER} (paired two-tailed t-test: df=10, t=-2.64, p=0.02, CV=2.23) (Table 2 and 3). This indicated algal growth anomalies' strong seasonal sunlight dependence reflecting *C. compactum*'s primary growing season in the summer.

Table 3

Results of regression analysis between algal anomalies and SST (R- and p-values)

Site	Mean SST _A (°C)	Correlations with growth anomalies						
		SST _A (Jan-Dec)		SST _M			SST _{SUMMER} (May-Oct)	
		R	p	Months (p<0.05)	R	p	R	p
Mosselbukta, NO	1.07	-0.24	0.15	Sep	0.44	0.006	-0.14	0.40
Aasiaat, GL	1.41	0.29	0.08	May	0.52	0.001	0.17	0.30
Qasigiannnguit, GL	1.41	-0.07	0.70	**	**	**	0.05	0.75
Upernavik, GL	0.81	0.47	0.004	Aug-Sep	0.42	0.02	0.39	0.009
Grady Island, NL	2.49	0.27	0.14	**	**	**	0.08	0.68
Kingitok Islands, NL	1.14	0.31	0.08	Jul-Sep	0.51	0.003	0.44	0.01
Qikiqtarjuaq, NU	-0.63	0.47	0.005	Jul-Oct	0.53	0.0002	0.50	0.002
Gulf of Boothia, NU	-1.36	0.28	0.1	Jul	0.39	0.02	0.27	0.1
Arctic Bay, NU	-0.94	0.03	0.88	**	**	**	0.03	0.88
Rigby Bay, NU	-0.86	0.16	0.36	Sep	0.39	0.02	0.15	0.38
Beechey Island, NU	-1.01	0.57	0.0002	May-Oct	0.56	0.0003	0.56	0.0003

Note. Monthly SST falling between May and October that individually produced significant and positive correlations to algal growth anomalies are labelled under SST_M: 'Months (p<0.05)'. Significant correlations (p<0.05) shaded orange. Sites with no significant correlating months indicated with two asterisks (**). Negative correlations shaded grey.

367

368 3.4 Temporal variability of algal - sea ice - temperature relationships

369

370 Temporal shifts in correlation between algal anomalies and SIC and SST were investigated
371 through the generation of 10-year running correlations. The temporal shift in correlation over the
372 past few decades indicated two overarching trends: 1) reduction of proxy strength in recent
373 decades due to the rapid reduction of sea ice; 2) increasing proxy strength in recent years due to
374 higher inter-annual sea ice variability (Figure 6). However, due to the short duration of records
375 and thus low sample size, many of the correlations are not significant (n=10/running correlation).

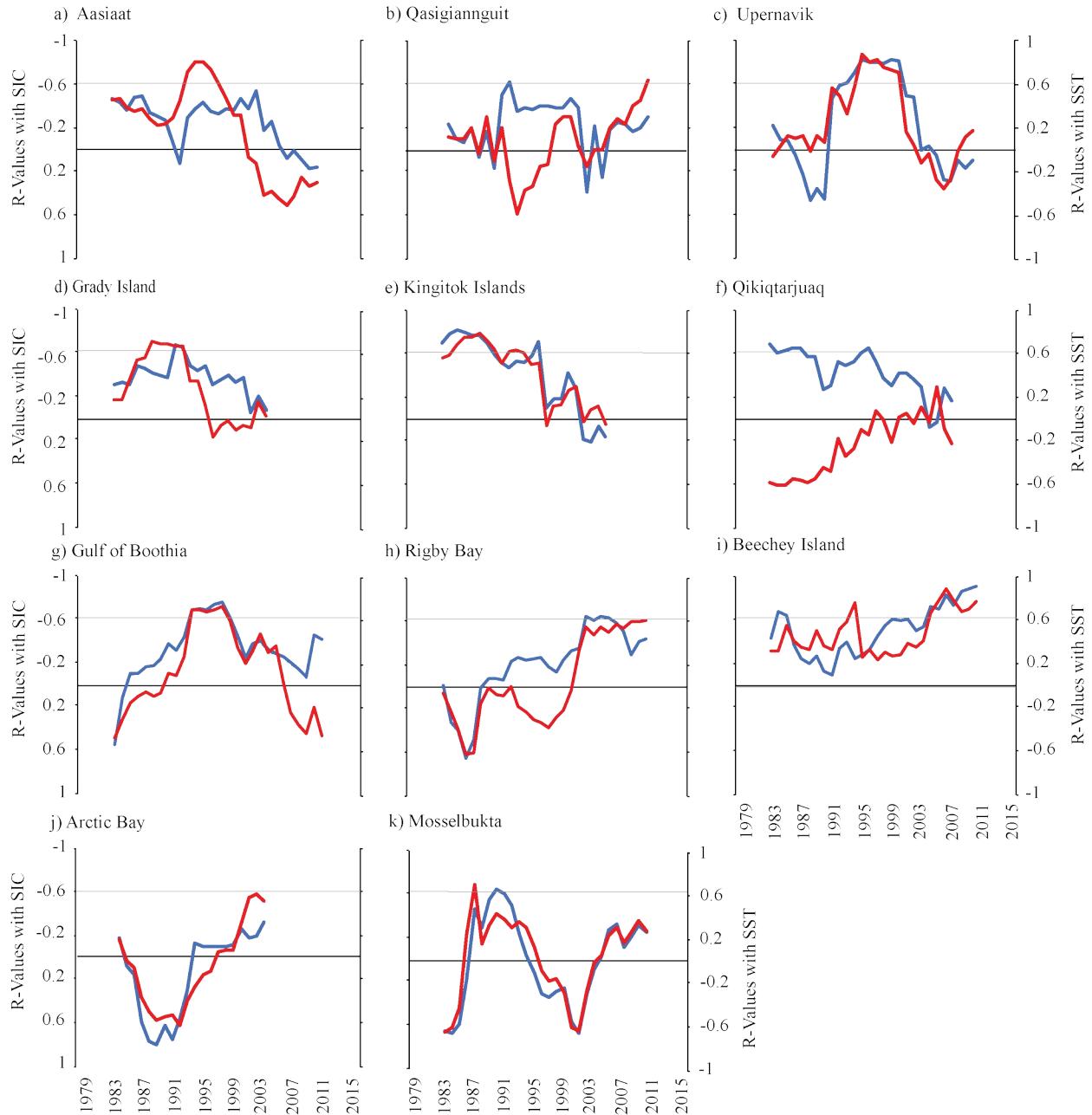


Figure 6. Results of 10-year running correlations with linear regression between algal growth anomalies and mean SST_{SUMMER} and SIC_{SUMMER} (May-Oct). Red line represents correlations with summer SST, and blue line represents correlation with summer SIC. Grey horizontal line indicates 95% significance threshold.

Algal anomalies in Aasiaat, Greenland, had strong correlations to SIC in the early record, followed by weaker correlations in the late record into the 2000s (Figure 6a). Notably, the late record is marked by increased inter-sample algal anomaly variability (Figure 4a). In addition,

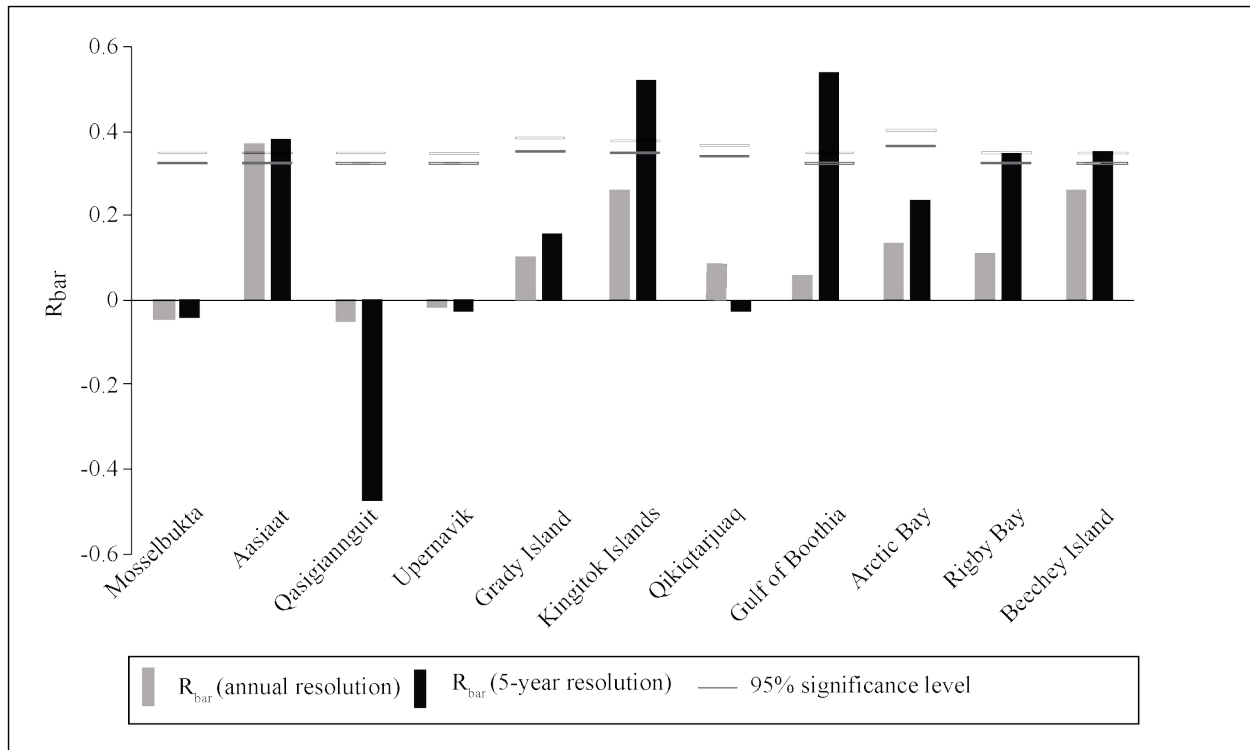
when comparing the relationship between SIC_{SUMMER} and growth time series (Figure 4b) and how it has changed through time at Qasigiannugit (Figure 6b), periods of low inter-annual SIC_{SUMMER} variability (1999-2015) produced algal anomalies that did not strongly correlate to sea ice records. Correlations with SIC_{SUMMER} were periodically stronger than SST_{SUMMER} in the earlier and mid-section of the satellite record, yet not significant, however the relationship with temperature has increased since the early 2000s (Figure 6b). Upernavik also had stronger algal-sea ice relationships in the early record, that weakened in the 1990s when sea ice became completely absent in July after 1996 (Figure 6c). Kingitok Islands and Grady Island (Figure 6d; 6e) results showed that correlations with SIC and SST were stronger in the early record than in the late record. Kingitok Islands and Grady Island experienced a significant reduction of sea ice after 1995. Accordingly, correlations with SIC_{SUMMER} and SST_{SUMMER} were stronger prior to 1995 and correlations are generally weaker in recent years as temperatures have been relatively stable and cloud cover has reduced. On the other hand, Qikiqtarjuaq, Gulf of Boothia, Rigby Bay and Beechey Island experienced a steady decline in SIC since the beginning of the satellite record but retained a higher concentration of sea ice for longer periods compared to other studied regions (Figure 4). Algal growth anomalies generally track the lower and higher ice years but cannot account for the full amplitude of sea ice variability and/or tend to have lower correlations during periods of low variability (Figure 4 and 6). Qikiqtarjuaq, Rigby Island and Beechey Island correlations to SIC were stronger after the 1980s, a period marked by higher variability of sea ice and algal growth anomalies (Figure 6f, 6h, 6i). Similar to Qasigiannugit, correlations at Qikiqtarjuaq of growth anomalies to SST have strengthened while those to SIC have decreased (Figure 6f). In the Gulf of Boothia, correlations to SIC are strongest in the mid-record when SIC and algal growth anomalies have high inter-annual variability (Figure 4g and 6g).

3.6 Inter-series variability

Synchrony of growth anomalies between samples from the same site was measured by first conducting linear regression tests between algal anomaly time series sample pairs, and averaging R-values together to express a site's inter-series correlation (R_{bar}), a statistic often used to express synchrony in dendro- and sclerochronology (e.g., Butler et al., 2009). While inter-series correlations at the annual level were only significant at one site, inter-series correlations were

416 significant at 5 sites when five-year running averages were used (Figure 7).

417



418

419 **Figure 7.** Inter-series correlation results (R_{bar}) at annual (grey) and five-year average (black)
 420 resolutions with corresponding 95% significance level threshold (dark grey: annual resolution;
 421 light grey: 5-year average resolution).

422 4 Discussion

423 4.1 Influence of runoff and degree of exposure on algal-ice relationships

424

425 Sites that significantly correlated with SIC_A and $\text{SIC}_{\text{SUMMER}}$ tend to be in relatively exposed
 426 regions, away from glacial and fluvial runoff sources. As was suggested by Adey et al. (2015)
 427 these mid-exposure habitats in terms of currents and waves would likely yield the longest-lived
 428 *C. compactum* specimens, as they would be affected by low levels of sedimentation and enough
 429 grazers to remove sedimentary detritus on algal surfaces. Accordingly, growth may be more
 430 affected by temperature or overlying sea ice if it is not impeded by grazers and/or sediment
 431 accumulation. Sites that are relatively exposed include Beechey Island, Gulf of Boothia,
 432 Qikiqtarjuaq, Kingitok Islands, and Upernavik as they are situated on islands away from the

coast or on peninsulas as opposed to embayments. Spatial correlation maps of these relatively exposed sites showed strong negative correlations to SIC in grid cells radiating around collection sites (Figure 5). This supports the hypothesis that *C. compactum* growth anomalies respond firstly to local SIC conditions and, by association, secondarily to regional SIC conditions. Slightly less exposed sites include Rigby Bay, Aasiaat and Qasigiannnguit which are located near the mouth of exposed bays. Algal growth increments are likely recording very localized light variation when their locations are more secluded such as the Arctic Bay site in the Canadian Arctic Archipelago. Arctic Bay's distance to more dynamic sea ice regions in the archipelago is distinct from other sites investigated, leading to a low energy environment with possible increased sediment buildup on the algae, thereby lowering receipt of light.

Furthermore, *C. compactum* samples are collected in nearshore environments, environments that become increasingly vulnerable to higher sediment discharge with warming conditions and reduced sea ice (Teichert & Freiwald, 2014). Accordingly, diminishing correlations between algal growth anomalies and SST and/or SIC instrumental records may be enhanced in regions near sediment runoff. Mosselbukta and Aasiaat experienced decreasing correlations with SIC particularly noticeable in the 1990s into the early 2000s (Figure 6a & 6k) as SIC significantly declined. While instrumental data for runoff is not available for Mosselbukta, Svalbard, modeled runoff data suggested increasing runoff in recent decades (Lang, Fettweis, & Erpicum, 2015; Möller & Kohler, 2018; Østby et al., 2017; van Pelt et al., 2016). Barium-calcium ratios (Ba/Ca) in coralline red algae have previously been used to reconstruct variability in runoff in nearshore environments (Chan et al., 2011). More recently, a study on *C. compactum* Ba/Ca from Mosselbukta effectively suggested a drastic increase in runoff since the late 1980s (Hetzinger, et al., 2021). This could have created more turbidity in the water column and less solar light transmission to the benthos, causing a recent reduction in increment widths in the Mosselbukta samples. The Aasiaat samples also exhibited a trend towards thinner growth increments in recent years, while reduction of SIC should have caused an increase in growth, and could therefore also be affected by increased sedimentation, especially due to the proximity to many glacial outputs related to the Jakobshavn glacier near Illullisat, Greenland.

4.2 Ice-on duration effect on algal response to sea ice conditions

464

465 Williams et al. (2018) suggested that light plays a more significant role in *C. compactum*'s
466 growth in warmer environments. While this may be true in ice-free regions with more balanced
467 light and temperature controls, the results of this study showed that algal growth anomalies from
468 regions with shorter ice-free seasons (i.e., shorter sunlight access) and lower sea surface
469 temperatures (Table 2 and 3) were better able to record light-inhibition by ice cover than regions
470 near the ice margin with longer ice-free seasons. This includes Beechey Island, Rigby Bay, Gulf
471 of Boothia, Qikiqtarjuaq, Upernavik and Kingitok Islands in the Canadian Arctic Archipelago
472 and on the central Labrador coast (Figure 2). Spatial correlation maps indicate that algal
473 anomalies from these sites have strong relationships with regional SIC and ocean currents
474 (Figure 5). Currents play a significant role in sea ice dynamics (Warn-Varnas, Allard, & Piacsek,
475 1991), causing similar sea ice conditions along them. Accordingly, these high correlation regions
476 indicate which regions may yield future samples useful to reconstruct regional sea ice.

477

478 Upernavik, Grady Island and Kingitok Islands have all encountered a significant reduction in the
479 length of the ice-free season. Upernavik has witnessed ice-free Julys since 1997, after which
480 correlations with both sea ice and temperature were reduced (Figure 6c). After 1997, there were
481 also marked reductions in algal growth increment variability and sea ice concentration (Figure
482 4c). This proceeded came after a positive Arctic Oscillation phase which decreased multi-year
483 ice coverage and coincided with abnormally warm air temperatures after 1996 which expedited
484 the rate of sea ice decline for the years to come (Overland & Wang, 2005). After the late 1990s,
485 algal growth anomalies became less variable reflected also by low and stable sea ice
486 concentrations. However, algal growth anomalies did not always match regional sea ice
487 variability suggesting that other factors may have affected algal growth variability. Sea surface
488 temperatures (SST) continued to increase and algal growth anomalies seemed to have responded
489 to SST peaks but failed to increase in amplitude (Supplementary Figure 1). According to a recent
490 study by He et al. (2019), cloud increased in the Upernavik region since the early 2000s.
491 Previous work on the coralline red algae species *Lithothamnion glaciale*, found an inverse
492 relationship between summer calcification and the previous winter's cloud cover in Scotland
493 (Burdett, Kamenos, & Law, 2011). Therefore, while sea ice concentrations have reduced around
494 Upernavik and produced a trend towards thicker growth increments, increased cloud cover may

have counteracted the effect of the longer ice-free season by dimming sunlight access to the sea floor, thereby reducing the inter-annual variability (i.e., amplitude) of growth increments (Figure 4c), and the correlation between sea ice and algal growth (Figure 6c) in the last decade of the record.

Similarly, in the early satellite record, ice-free conditions started in July and ended in November in the Kingitok Islands. However, after the early 2000s, the region was ice-free by June lasting until December in some years causing longer ice-free periods. The reduction of sea ice may have disrupted the previously stronger sea ice relationship with algal growth. Results of 10-year running correlations show that SIC_{SUMMER} and SST_{SUMMER} correlations with algal growth anomalies declined in the 2000s likely as a result of the lengthening of the ice-free period (Figure 6e). In the late record, algal anomalies no longer matched SIC variability but continued to match the trend towards less sea ice (larger increments) (Figure 4e). The region experienced relatively stable summer sea surface temperatures (1979-2010, June-July), while summer cloud cover reduced (-2.65% per decade, 1982-2010). Accordingly, the reduction of cloud cover would have increased the sunlight irradiance reaching algal specimens and may have produced larger increments in lower SIC years and increased the inter-annual variability of sunlight-driven growth.

On the other hand, while algal growth anomalies from Grady Island weakly correlated with the trend of instrumental records (Tables 2 and 3), they produced negative 10-year running correlations with SIC_{SUMMER} and SST_{SUMMER} (Figure 6a), suggesting they responded to sea ice variability. Since linear regressions are sensitive to trends, the fact that algal growth anomalies showed a strong trend towards smaller increments in the 2000s while deteriorating sea ice conditions typically bolster the formation of larger increments suggested that factors other than SST and SIC limited algal growth in recent time. Regional phytoplankton productivity time series (Glen Harrison et al., 2013) and chlorophyll α concentration from MODIS/Aqua satellite records suggested that the amplitude of algal anomalies may have been affected by summer phytoplankton productivity-caused turbidity. Years with higher summer Chlorophyll α concentrations often occur simultaneously with lower algal growth anomalies. Barium-calcium ratio and carbon isotopes time series derived from *C. compactum* have previously established the

relationship between coralline red algae geochemistry (Ba/Ca and $\delta^{13}\text{C}$) and sea ice driven productivity variability (Chan et al., 2017). Due to the relationship between algal growth and light availability, it is likely that turbidity caused by large phytoplankton blooms may have affected the amplitude of algal growth anomalies especially in regions with longer ice-free seasons.

In addition, algal growth anomalies from regions that experienced significant reductions in sea ice cover may shift from being sea ice dependent to being temperature dependent, as exhibited by the Qasigiannguut and Qikiqtarjuaq samples, while previously higher concentrations and longer duration of sea ice may produce stronger algal-sea ice relationships. Previous studies examined the multi-centennial Mosselbukta algal time series and revealed a strong relationship between combined algal anomalies and sea ice cover from the early 20th century to the early 2000s (Hetzinger et al., 2019), demonstrating that the algal sea ice proxy had a higher recording strength during periods and in regions of longer sea ice cover duration. Therefore, sea ice may have variable control on algal growth anomalies depending on the length of the open water season, when the annual solar insolation cycle, temperature and other light inhibiting variables exert a stronger influence on algal growth, especially for sites closer to the margins of the ice pack. In some regions, longer open water durations have produced large phytoplankton blooms and increased cloud cover which could further obscure light reaching the seafloor and influence *C. compactum* growth and geochemistry (Arrigo, van Dijken, & Pabi, 2008; Chan et al., 2017; He et al., 2019). On the other hand, shorter ice-free periods may limit the effect light inhibitors (excluding sea ice) have on annual algal growth anomalies.

4.3 Spatial resolution bias of the satellite record

Typically, the ice-free season is defined as less than 15% sea ice concentration (Ridley, et al., 2016), providing a warmer open water period when photosynthetic growth of *C. compactum* should be occurring (Adey, 1970; Williams et al., 2018). However, the data from this study suggested that *C. compactum* grew and recorded SIC during months with higher than 15% sea ice cover over the 75 km² gridded area (Figure 4). For example, regions such as Lancaster Sound near Beechey Island had the strongest negative correlation of all sites (Table 2, Figure 5), but has

seldom recorded monthly means lower than 30% SIC over the study period. A 1° spatial resolution SIC time series provided by the KNMI Climate Explorer tool revealed that months with the strongest negative correlations at Beechey Island occurred during low SIC months (i.e., May-Oct) but SIC levels were rarely below 15% (Reynolds, et al., 2002). Further, NASA satellite images showed ice breakup around Beechey Island by late July that was cleared of ice by early August (2002-2015) suggesting that the lack of correlation between ice-free day/year and algal growth anomalies (Table 2) may be caused by an inaccurate representation of local ice-free and ice-on days in the 75 km² gridded satellite cell. Further, some issues regarding early sensors and data homogenization (National Center for Atmospheric Research Staff, 2019) may have challenged the comparison of satellite-derived SIC to algal anomalies as early satellite imagery was unable to capture SIC in small channels and bays due to the presence of land within large 25 km² grid cells (Howell, Duguay, & Markus, 2009). This is particularly noticeable in the region around Arctic Bay, where satellite imagery showed some discrepancies in timing of ice formation and breakup between the secluded setting of Arctic Bay and the adjacent larger inlet which offered the nearest gridded SIC data (Supplemental Figure 2).

4.4 Temporal resolution of algal-ice relationship

The measure of ice-free days consists of very high-resolution temporal data; however, algae likely start growing well before the database records <15% sea ice concentrations. Similarly, photosynthetic phytoplankton start blooming while the ice is thin, uncovered by snow and full of melt ponds (Massicotte et al., 2020) while daily satellite records would still record ice cover (<15%). This may explain why few correlations were found between annual growth anomalies and ice-free days. In addition, correlations with SIC were appreciably stronger when both growth increment and SIC measurements were downsampled to 5-year running means (Table 2). *C. compactum*'s growth increments have previously been shown to correlate well to long-term regional sea ice decline over at least the past century (Halfar et al., 2013; Hetzinger et al., 2019). Therefore, while able to record SIC on an annual scale, *C. compactum*'s may be better suited to reconstruct SIC variability on a multi-year average scale (Hetzinger et al., 2019). The reasons for this likely are that other light inhibitors such as sedimentation, phytoplankton blooms and cloud cover may have affected the amplitude of algal anomalies for any given year. Therefore, 5-year

running averages may smooth out the impact of these other light-related variables. Furthermore, five-year running means of algal growth time series produced significant inter-series correlations at 5 sites, in comparison to 1 at an annual resolution (Figure 7). This suggested that either multi-year averages reduced individual noise and isolated the climate signal or that multiyear averages smoothed potential age model errors that may have reduced inter-series correlations at the annual level.

4.5 Inter-sample variability

Uncertainties remain about how the number of algal samples included in site averages affects the strength of the sea ice-algal proxy relationship. In this study all analyzed samples were included in calculating algal growth anomalies, however the results clearly convey the variability between samples and that poor inter-series correlations may have affected the final algal correlation with sea ice conditions (Figure 6). Williams et al. (2014) suggested that inter-sample variability might be caused by variation in micro-environments (e.g., sample positioning relative to shading on the seafloor). On the other hand, Marali and Schöne (2015), who studied growth increments from the North Atlantic bivalve *Arctica islandica*, suggested that periods of low inter-annual variability could cause proxy time series from different samples to become desynchronized by factors affecting the organism at the individual level. Accordingly, Aasiaat and Qasigiannnguit algal samples experienced reduced inter-annual summer SST variability (Jun-Jul) in recent record years. Simultaneously, higher inter-sample growth variability was observed (Figure 4). During low inter-annual climate variability, individual algal samples may be affected by differential predation pressures from chitons and urchins, physical disturbances, and competitive overgrowth may cause growth anomalies and consequent growth variability between samples (Adey et al., 2013). It is important to note that some samples produced synchronous algal growth anomalies, while the averaged inter-series correlation for the entire site was reduced significantly if a less synchronous sample was integrated in the average. Therefore, it will be important to focus on synchronous samples with a shared environmental signal when using *C. compactum* as a past sea ice proxy.

In this study two to three samples per site were averaged, with the exception of Mosselbukta where five samples were averaged. In other proxy studies, the number of samples used is dependent on the proxy archive. Sediment core-based studies often rely on a single well-dated core sample (e.g., (Berben, et al., 2017; Eiriksson et al., 2011)). Coral-based proxy time series are also typically generated from a single core sample from each site (e.g., Calvo et al., 2007; Tierney et al., 2015) due to the high cost of geochemical analysis and time involved to prepare and process data (Corrège, 2006). However, multi-sample proxy studies are becoming more common to increase replication, proxy signal strength and reliability (DeLong, et al., 2013; Jones et al., 2009; von Reumont, et al., 2016). Hetzinger et al. (2018) showed high replicability of Mg/Ca ratios down-sampled to 12 measurements/year from nine *C. compactum* sample collected in the Gulf of Maine, an ice-free region with larger growth increments, indicating their common climate signal. This theoretically suggests that only one algal sample could be used to build a time series. Conversely, colder and light-limited regions of the Arctic are more likely to produce thinner increments with unclear boundaries during high sea ice cover years which could introduce errors in age model construction. The results of 10-year running correlations at sites with long sea ice duration and high sea ice concentrations (i.e., Rigby Bay, Beechey Island, Gulf of Boothia) showed a reduction in correlation with instrumental SIC and SST records further back in time, suggesting possible errors propagated later into the record due to the thinner increments more easily missed when growth rates are slower in high SIC and colder periods. Further incorporation of cross-dating methods in age model construction may help diagnose synchrony problems and identify samples that should be excluded from *C. compactum*-based proxy reconstructions.

5 Conclusions

This is the first multi-sample study investigating the relationship between algal anomalies of *Clathromorphum compactum* (Mg/Ca, growth increment, and combined anomalies) and sea ice cover at multiple sites in the Arctic and Subarctic obtained from high spatial resolution satellite datasets. The results of this study showed that correlations between algal growth anomalies and sea ice concentration are stronger in regions/periods of higher sea ice concentrations, longer ice-on seasons, and reduced runoff and turbidity. Accordingly, our results yield important information for the identification of ideal study sites for future sea ice reconstructions. Annual

648 algal growth anomalies may be sufficient, instead of combined algal anomalies or Mg/Ca ratios
649 alone, to show relative change in sea ice conditions at sites where algal anomalies respond more
650 predictably to year-to-year sea ice variability. However, the algal growth proxy recorded SIC
651 more strongly at most sites when downsampled to a five-year running mean and may therefore
652 produce better reconstructions on a multi-year average scale. Spatial correlation maps showed
653 that algal growth anomalies generally inversely correlated to regional SIC variability at most
654 sites. Weaker correlations between growth increment anomalies and sea ice conditions may be
655 related to differential exposure, turbidity, and lengthening of the ice-free season in the past two
656 decades, while correlations with sea ice cover in earlier, higher sea ice cover periods prior to
657 1979 were likely stronger (e.g., Hetzinger et al., 2019). Furthermore, algal growth anomalies
658 from regions that experienced significant reductions in sea ice cover may shift from being sea ice
659 dependent to being temperature dependent. Questions remain regarding variability between
660 samples and their timeseries as some sites tended to have low inter-series correlations.
661 Synchronous growth within sites should be a requirement to reconstruct annually-resolved sea
662 ice conditions of the past. The significant correlations between algal growth anomalies and SIC
663 highlight the opportunity *C. compactum* can provide as an *in situ* marine high-resolution ice
664 cover proxy.

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Data

The data on which this article is based contains original data in combination with previously published data which are available in Halfar et al. (2013) and Hetzinger et al. (2019). Original datasets will be published through the NOAA National Centers for Environmental Information Paleoclimatology Data Repository (<https://www.ncei.noaa.gov/pub/data/paleo/>) upon acceptance. Primary datasets for this research are also included in figures and supplementary information files.

References

- Adey, W. (1965). The genus *Clathromorphum* (Corallinaceae) in the Gulf of Maine. *Hydrobiologia*, 26(3–4), 539–573.
- Adey, W. H. (1970). The effects of light and temperature on growth rates in boreal–subarctic crustose corallines. *Journal of Phycology*, 6(3), 269–276.
- Adey, W. H., Halfar, J., & Williams, B. (2013). *The Coralline Genus Clathromorphum Foslief emend. Adey: Biological, Physiological, and Ecological Factors Controlling Carbonate Production in an Arctic-Subarctic Climate Archive*. Washington DC: Smithsonian Institution Scholarly Press.
- Adey, W., Halfar, J., Humphreys, A., Suskiewicz, T., Belanger, D., Gagnon, P., & Fox, M. (2015). Subarctic rhodolith beds promote longevity of crustose coralline algal buildups and their climate archiving potential. *Palaaios*, 30(4), 281–293.
- Arrigo, K. R., van Dijken, G., & Pabi, S. (2008). Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters*, 35(19). <https://doi.org/10.1029/2008GL035028>

- Backman, J., Jakobsson, M., Løvlie, R., Polyak, L., & Febo, L. A. (2004). Is the central Arctic Ocean a sediment starved basin? *Quaternary Science Reviews*, 23(11–13), 1435–1454.
<https://doi.org/10.1016/J.QUASCIREV.2003.12.005>
- Belt, S. T. (2019). What do IP25 and related biomarkers really reveal about sea ice change? *Quaternary Science Reviews*, 204, 216–219.
<https://doi.org/10.1016/J.QUASCIREV.2018.11.025>
- Belt, S. T., Brown, T. A., Rodriguez, A. N., Sanz, P. C., Tonkin, A., & Ingle, R. (2012). A reproducible method for the extraction, identification and quantification of the Arctic sea ice proxy IP25 from marine sediments. *Analytical Methods*, 4(3), 705.
<https://doi.org/10.1039/c2ay05728j>
- Belt, S. T., Massé, G., Rowland, S. J., Poulin, M., Michel, C., & LeBlanc, B. (2007). A novel chemical fossil of palaeo sea ice: IP25. *Organic Geochemistry*, 38(1), 16–27.
<https://doi.org/10.1016/J.ORGGEOCHEM.2006.09.013>
- Berben, S. M. P., Husum, K., Navarro-Rodriguez, A., Belt, S. T., & Aagaard-Sørensen, S. (2017). Semi-quantitative reconstruction of early to late Holocene spring and summer sea ice conditions in the northern Barents Sea. *Journal of Quaternary Science*, 32(5), 587–603.
<https://doi.org/10.1002/jqs.2953>
- Burdett, H., Kamenos, N. A., & Law, A. (2011). Using coralline algae to understand historic marine cloud cover. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 302(1), 65–70.
<https://doi.org/10.1016/j.palaeo.2010.07.027>
- Butler, P. G., Scourse, J. D., Richardson, C. A., Wanamaker, A. D., Bryant, C. L., & Bennell, J. D. (2009). Continuous marine radiocarbon reservoir calibration and the 13C Suess effect in the Irish Sea: Results from the first multi-centennial shell-based marine master chronology. *Earth and Planetary Science Letters*, 279(3–4), 230–241.
<https://doi.org/10.1016/j.epsl.2008.12.043>
- Calvo, E., Marshall, J. F., Pelejero, C., McCulloch, M. T., Gagan, M. K., & Lough, J. M. (2007). Interdecadal climate variability in the Coral Sea since 1708 A.D. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 248(1–2), 190–201.
<https://doi.org/10.1016/j.palaeo.2006.12.003>
- Cavalieri, D. J., & Parkinson, C. L. (2012). Arctic sea ice variability and trends, 1979-2010. *The Cryosphere*, 6(4), 881–889. <https://doi.org/https://doi.org/10.5194/tc-6-881-2012>, 2012.

- 725 Chan, P., Halfar, J., Adey, W., Hetzinger, S., Zack, T., Moore, G. W. K., et al. (2017).
726 Multicentennial record of Labrador Sea primary productivity and sea-ice variability
727 archived in coralline algal barium. *Nature Communications*, 8(1), 1–10.
728 <https://doi.org/10.1038/ncomms15543>
- 729 Chan, Phoebe, Halfar, J., Williams, B., Hetzinger, S., Steneck, R., Zack, T., & Jacob, D. E.
730 (2011). Freshening of the Alaska Coastal Current recorded by coralline algal Ba/Ca ratios.
731 *Journal of Geophysical Research*, 116(G1), G01032.
732 <https://doi.org/10.1029/2010JG001548>
- 733 Comiso, J. C., Meier, W. N., & Gersten, R. (2017). Variability and trends in the Arctic Sea ice
734 cover: Results from different techniques. *Journal of Geophysical Research: Oceans*, 122(8),
735 6883–6900. <https://doi.org/10.1002/2017JC012768>
- 736 Corrège, T. (2006). Sea surface temperature and salinity reconstruction from coral geochemical
737 tracers. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 232(2–4), 408–428.
738 <https://doi.org/10.1016/j.palaeo.2005.10.014>
- 739 De Vernal, A., Gersonde, R., Goosse, H., Seidenkrantz, M. S., & Wolff, E. W. (2013). Sea ice in
740 the paleoclimate system: The challenge of reconstructing sea ice from proxies - an
741 introduction. *Quaternary Science Reviews*, 79, 1–8.
742 <https://doi.org/10.1016/j.quascirev.2013.08.009>
- 743 DeLong, K. L., Quinn, T. M., Taylor, F. W., Shen, C. C., & Lin, K. (2013). Improving coral-base
744 paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations.
745 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 373, 6–24.
746 <https://doi.org/10.1016/j.palaeo.2012.08.019>
- 747 Ding, Q., Schweiger, A., L’Heureux, M., Battisti, D. S., Po-Chedley, S., Johnson, N. C., et al.
748 (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic
749 sea ice. *Nature Climate Change*, 7(4), 289–295. <https://doi.org/10.1038/nclimate3241>
- 750 Eiríksson, J., Knudsen, K. L., Larsen, G., Olsen, J., Heinemeier, J., Bartels-Jónsdóttir, H. B., et
751 al. (2011). Coupling of palaeoceanographic shifts and changes in marine reservoir ages off
752 North Iceland through the last millennium. *Palaeogeography, Palaeoclimatology,*
753 *Palaeoecology*, 302(1), 95–108. <https://doi.org/10.1016/j.palaeo.2010.06.002>
- 754 Foster, M. S. (2001). Rhodoliths: Between rocks and soft places. *Journal of Phycology*, 37(5),
755 659–667. <https://doi.org/10.1046/j.1529-8817.2001.00195.x>

- Gemery, L., Cronin, T. M., Briggs, W. M., Brouwers, E. M., Schornikov, E. I., Stepanova, A., et al. (2017). An Arctic and Subarctic ostracode database: biogeographic and paleoceanographic applications. *Hydrobiologia*, 786(1), 59–95. <https://doi.org/10.1007/s10750-015-2587-4>
- Glen Harrison, W., Yngve Børsheim, K., Li, W. K. W., Maillet, G. L., Pepin, P., Sakshaug, E., et al. (2013). Phytoplankton production and growth regulation in the Subarctic North Atlantic: A comparative study of the Labrador Sea-Labrador/Newfoundland shelves and Barents/Norwegian/Greenland seas and shelves. *Progress in Oceanography*, 114, 26–45. <https://doi.org/10.1016/j.pocean.2013.05.003>
- Halfar, J., Adey, W. H., Kronz, A., Hetzinger, S., Edinger, E., & Fitzhugh, W. W. (2013). Arctic sea-ice decline archived by multicentury annual-resolution record from crustose coralline algal proxy. *Proceedings of the National Academy of Sciences*, 110(49), 19737–19741. <https://doi.org/10.1073/pnas.1313775110>
- He, M., Hu, Y., Chen, N., Wang, D., Huang, J., & Stamnes, K. (2019). High cloud coverage over melted areas dominates the impact of clouds on the albedo feedback in the Arctic. *Scientific Reports*, 9(1), 1–11. <https://doi.org/10.1038/s41598-019-44155-w>
- Hetzinger, S., Halfar, J., Kronz, A., Simon, K., Adey, W. H., & Steneck, R. S. (2018). Reproducibility of *Clathromorphum compactum* coralline algal Mg/Ca ratios and comparison to high-resolution sea surface temperature data. *Geochimica et Cosmochimica Acta*, 220, 96–109.
- Hetzinger, S., Halfar, J., Zack, T., Gamboa, G., Jacob, D. E., Kunz, B. E., et al. (2011). High-resolution analysis of trace elements in crustose coralline algae from the North Atlantic and North Pacific by laser ablation ICP-MS. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 302(1), 81–94. <https://doi.org/10.1016/j.palaeo.2010.06.004>
- Hetzinger, Steffen, Halfar, J., Zajacz, Z., Möller, M., & Wisshak, M. (2021). Late twentieth century increase in northern Spitsbergen (Svalbard) glacier-derived runoff tracked by coralline algal Ba/Ca ratios. *Climate Dynamics*, 1, 3. <https://doi.org/10.1007/s00382-021-05642-x>
- Hetzinger, Steffen, Halfar, J., Zajacz, Z., & Wisshak, M. (2019). Early start of 20th-century Arctic sea-ice decline recorded in Svalbard coralline algae. *Geology*, 47(10), 963–967. <https://doi.org/10.1130/G46507.1>

- 787 Hill, B. T., & Jones, S. J. (1990). The Newfoundland ice extent and the solar cycle from 1860 to
788 1988. *Journal of Geophysical Research*, 95(C4), 5385.
789 <https://doi.org/10.1029/JC095iC04p05385>
- 790 Howell, S. EL, Duguay, C. R., & Markus, T. (2009). Sea ice conditions and melt season duration
791 variability within the Canadian Arctic Archipelago: 1979–2008. *Geophysical Research*
792 *Letters*, 36(10). <https://doi.org/10.1029/2009GL037681>
- 793 Jones, P. D., Briffa, K. R., Osborn, T. J., Lough, J. M., Van Ommen, T. D., Vinther, B. M., et al.
794 (2009). High-resolution palaeoclimatology of the last millennium: A review of current
795 status and future prospects. *Holocene*, 19(1), 3–49.
796 <https://doi.org/10.1177/0959683608098952>
- 797 Kaufman, D. S. (2009). An overview of late Holocene climate and environmental change
798 inferred from Arctic lake sediment. *Journal of Paleolimnology*, 41(1), 1–6.
799 <https://doi.org/10.1007/s10933-008-9259-6>
- 800 Kinnard, C., Zdanowicz, C. M., Fisher, D. A., Isaksson, E., de Vernal, A., & Thompson, L. G.
801 (2011). Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature*, 479, 509–
802 513.
- 803 Köseoğlu, D., Belt, S. T., Husum, K., & Knies, J. (2018). An assessment of biomarker-based
804 multivariate classification methods versus the PIP25 index for paleo Arctic sea ice
805 reconstruction. *Organic Geochemistry*, 125, 82–94.
806 <https://doi.org/10.1016/j.orggeochem.2018.08.014>
- 807 Kucera, M., Weinelt, M., Kiefer, T., Pflaumann, U., Hayes, A., Weinelt, M., et al. (2005).
808 Reconstruction of sea-surface temperatures from assemblages of planktonic foraminifera:
809 multi-technique approach based on geographically constrained calibration data sets and its
810 application to glacial Atlantic and Pacific Oceans. *Quaternary Science Reviews*, 24, 951–
811 998. <https://doi.org/10.1016/j.quascirev.2004.07.014>
- 812 Lang, C., Fettweis, X., & Erpicum, M. (2015). Stable climate and surface mass balance in
813 Svalbard over 1979–2013 despite the Arctic warming. *Cryosphere*, 9(1), 83–101.
814 <https://doi.org/10.5194/tc-9-83-2015>
- 815 Mahoney, A. R., Bockstoe, J. R., Botkin, D. B., Eicken, H., & Nisbet, R. A. (2011). Sea-Ice
816 distribution in the Bering and Chukchi seas: Information from historical whaleships’
817 logbooks and journals. *Arctic*, 64(4), 465–477. Retrieved from

- 818 <http://www.jstor.org/stable/41319241>
- 819 Marali, S., & Schöne, B. R. (2015). Oceanographic control on shell growth of *Arctica islandica*
820 (*Bivalvia*) in surface waters of Northeast Iceland — Implications for paleoclimate
821 reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 420, 138–149.
822 <https://doi.org/10.1016/j.palaeo.2014.12.016>
- 823 Massicotte, P., Amiriaux, R., Amyot, M. P., Archambault, P., Ardyna, M., Arnaud, L., et al.
824 (2020). Green edge ice camp campaigns: Understanding the processes controlling the
825 under-ice arctic phytoplankton spring bloom. *Earth System Science Data*, 12(1), 151–176.
826 <https://doi.org/10.5194/essd-12-151-2020>
- 827 Meier, W. N., Fetterer, F., Savoie, M., Mallory, S., Duerr, R., & Stroeve, J. (2017).
828 *NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration*. Boulder,
829 Colorado: NSIDC: National Snow and Ice Data Center.
830 <https://doi.org/https://doi.org/10.7265/N59P2ZTG>
- 831 Meier, Walter N., Hovelsrud, G. K., Van Oort, B. E. H., Key, J. R., Kovacs, K. M., Michel, C., et
832 al. (2014). Arctic sea ice in transformation: A review of recent observed changes and
833 impacts on biology and human activity. *Reviews of Geophysics*, 52(3), 185–217.
834 <https://doi.org/10.1002/2013RG000431>
- 835 Melling, H. (2002). Sea ice of the northern Canadian Arctic Archipelago. *Journal of Geophysical*
836 *Research: Oceans*, 107(11), 2–1. <https://doi.org/10.1029/2001jc001102>
- 837 Möller, M., & Kohler, J. (2018). Differing climatic mass balance evolution across Svalbard
838 glacier regions over 1900–2010. *Frontiers in Earth Science*, 6, 128. <https://doi.org/10.3389/feart.2018.00128>
- 839 Müller, J., Wagner, A., Fahl, K., Stein, R., Prange, M., & Lohmann, G. (2011). Towards
840 quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker
841 and numerical modelling approach. *Earth and Planetary Science Letters*, 306(3–4), 137–
842 148. <https://doi.org/10.1016/J.EPSL.2011.04.011>
- 843 National Center for Atmospheric Research Staff. (2019). The Climate Data Guide: Sea Ice
844 Concentration data from NOAA OI. Retrieved February 10, 2019, from Climate Data Guide
845 website: <https://climatedataguide.ucar.edu/climate-data/sea-ice-concentration-data-noaa-oi>
846 Østby, T. I., Vikhamar Schuler, T., Ove Hagen, J., Hock, R., Kohler, J., & Reijmer, C. H. (2017).
847 Diagnosing the decline in climatic mass balance of glaciers in Svalbard over 1957–2014.

- 849 *Cryosphere*, 11(1), 191–215. <https://doi.org/10.5194/tc-11-191-2017>
- 850 Overland, J. E., & Wang, M. (2005). The Arctic climate paradox: The recent decrease of the
851 Arctic Oscillation. *Geophysical Research Letters*, 32(6), L06701.
852 <https://doi.org/10.1029/2004GL021752>
- 853 Peng, G., Meier, W. N., Scott, D. J., & Savoie, M. H. (2013). A long-term and reproducible
854 passive microwave sea ice concentration data record for climate studies and monitoring.
855 *Earth System Science Data*, 5(2), 311–318. <https://doi.org/10.5194/essd-5-311-2013>
- 856 Polyak, L., Alley, R. B., Andrews, J. T., Brigham-Grette, J., Cronin, T. M., Darby, D. A., et al.
857 (2010). History of sea ice in the Arctic. *Quaternary Science Reviews*, 29(15–16), 1757–
858 1778. <https://doi.org/10.1016/j.quascirev.2010.02.010>
- 859 Ran, L., Jiang, H., Knudsen, K. L., & Eiríksson, J. (2011). Diatom-based reconstruction of
860 palaeoceanographic changes on the North Icelandic shelf during the last millennium.
861 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 302(1), 109–119.
862 <https://doi.org/10.1016/j.palaeo.2010.02.001>
- 863 Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al.
864 (2003). Global analyses of sea surface temperature, sea ice, and night marine air
865 temperature since the late nineteenth century. *Journal of Geophysical Research*, 108(D14),
866 4407. <https://doi.org/10.1029/2002JD002670>
- 867 Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., & Wang, W. (2002). An improved
868 in situ and satellite SST analysis for climate. *Journal of Climate*, 15(13), 1609–1625.
869 [https://doi.org/10.1175/1520-0442\(2002\)015<1609:AIISAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2)
- 870 Ridley, J. K., Wood, R. A., Keen, A. B., Blockley, E., & Lowe, J. A. (2016). Brief
871 Communication: Does it matter exactly when the Arctic will become ice-free? *The*
872 *Cryosphere Discussions*, 1–4. <https://doi.org/10.5194/tc-2016-28>
- 873 Seidenkrantz, M.-S. (2013). Benthic foraminifera as palaeo sea-ice indicators in the subarctic
874 realm – examples from the Labrador Sea–Baffin Bay region. *Quaternary Science Reviews*,
875 79, 135–144. <https://doi.org/10.1016/J.QUASCIREV.2013.03.014>
- 876 Sicre, M. A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., et al. (2008). Decadal variability
877 of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary*
878 *Science Letters*, 268(1–2), 137–142. <https://doi.org/10.1016/j.epsl.2008.01.011>
- 879 Sicre, M. A., Yiou, P., Eiríksson, J., Ezat, U., Guimbaut, E., Dahhaoui, I., et al. (2008). A 4500-

- year reconstruction of sea surface temperature variability at decadal time-scales off North
Iceland. *Quaternary Science Reviews*, 27(21–22), 2041–2047.
<https://doi.org/10.1016/j.quascirev.2008.08.009>
- Stein, R., & Fahl, K. (2013). Biomarker proxy shows potential for studying the entire Quaternary
Arctic sea ice history. *Organic Geochemistry*, 55, 98–102.
<https://doi.org/10.1016/J.ORGGEOCHEM.2012.11.005>
- Teichert, S., & Freiwald, A. (2014). Polar coralline algal CaCO₃-production rates correspond to
intensity and duration of the solar radiation. *Biogeosciences*, 11(3), 833–842.
<https://doi.org/10.5194/bg-11-833-2014>
- Tierney, J. E., Abram, N. J., Anchukaitis, K. J., Evans, M. N., Giry, C., Kilbourne, K. H., et al.
(2015). Tropical sea surface temperatures for the past four centuries reconstructed from
coral archives. *Paleoceanography*, 30(3), 226–252. <https://doi.org/10.1002/2014PA002717>
- van Pelt, W. J. J., Kohler, J., Liston, G. E., Hagen, J. O., Luks, B., Reijmer, C. H., & Pohjola, V.
A. (2016). Multidecadal climate and seasonal snow conditions in Svalbard. *Journal of
Geophysical Research: Earth Surface*, 121(11), 2100–2117.
<https://doi.org/10.1002/2016JF003999>
- von Reumont, J., Hetzinger, S., Garbe-Schönberg, D., Manfrino, C., & Dullo, W.-C. (2016).
Impact of warming events on reef-scale temperature variability as captured in two Little
Cayman coral Sr/Ca records. *Geochemistry, Geophysics, Geosystems*, 17(3), 846–857.
<https://doi.org/10.1002/2015GC006194>
- Walsh, J. E., Fetterer, F., Stewart, S. J., & Chapman, W. L. (2017). A database for depicting
Arctic sea ice variations back to 1850. *Geographical Review*, 107(1), 89–107.
<https://doi.org/10.1111/j.1931-0846.2016.12195.x>
- Warn-Varnas, A., Allard, R., & Piacsek, S. (1991). Synoptic and seasonal variations of the ice-
ocean circulation in the Arctic: a numerical study. *Annals of Glaciology*, 15, 54–62. <https://doi.org/10.1017/s026030550000954x>
- Williams, B., Halfar, J., DeLong, K. L., Hetzinger, S., Steneck, R. S., & Jacob, D. E. (2014).
Multi-specimen and multi-site calibration of Aleutian coralline algal Mg/Ca to sea surface
temperature. *Geochimica et Cosmochimica Acta*, 139, 190–204.
<https://doi.org/10.1016/j.gca.2014.04.006>
- Williams, S., Adey, W. H., Halfar, J., Kronz, A., Gagnon, P., Bélanger, D., & Nash, M. (2018).

911 Effects of light and temperature on Mg uptake, growth, and calcification in the proxy
912 climate archive *Clathromorphum compactum*. *Biogeosciences*, 15(19), 5745–5759.
913 Worley, S. J., Woodruff, S. D., Reynolds, R. W., Lubker, S. J., & Lott, N. (2005). ICOADS
914 Release 2.1 Data and Products. *International Journal of Climatology*, 25, 823–842. [https://](https://doi.org/10.1002/joc.1166)
915 doi.org/10.1002/joc.1166
916