# Growth increments of coralline red alga Clathromorphum compactum capture sea-ice variability links to Atlantic Multidecadal and Arctic Oscillations (1805 - 2015)

Natasha Leclerc[1], Jochen Halfar[1], Steffen Hetzinger[2], Alexandra Tsay[3], and G. W. K. Moore[4]

[1]University of Toronto at Mississauga
[2]GEOMAR Helmholtz-Zentrum für Ozeanforschung
[3]University of Geneva
[4]University of Toronto

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**Abstract**

The Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), and related North Atlantic Oscillation (NAO) have been linked to multidecadal, decadal, and/or interannual sea-ice variability in the arctic, but their relative influences are still under evaluation. While instrumental AMO and reliable AO records are available since the mid-1800s and 1958, respectively, satellite sea-ice concentration datasets start only in 1979, limiting the shared timespan to study their interplay. Growth increments of the coralline algae, Clathromorphum compactum, can provide sea-ice proxy information for years prior to 1979. We present a seasonal 210-year algal record from Lancaster Sound in the Canadian Arctic Archipelago capturing low frequency AMO variability and high frequency interannual AO/NAO prior to 2000. We suggest that sea-ice variability here is strongly coupled to these large-scale climate processes, and that sea-ice cover was greater and the AO more negative in the early and late 19th century compared to the 20th.

# Growth increments of coralline red alga *Clathromorphum compactum* capture sea-ice variability links to Atlantic Multidecadal and Arctic Oscillations (1805 – 2015)

**N. Leclerc[1,2], J. Halfar[1], S. Hetzinger[3], A. Tsay[4], and G. W. K. Moore[1]**

[1] Chemical and Physical Sciences Department, University of Toronto Mississauga, 3359 Mississauga Road N., Ontario, L5L 1C6, Canada

[2] Department of Archaeology, Memorial University of Newfoundland, 210 Prince Philip Dr., Newfoundland & Labrador, A1C 5S7

[3] Christian-Albrechts-Universität zu Kiel, Institut für Geowissenschaften, Ludewig-Meyn-Str. 10, 24118 Kiel, Germany

[4] Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, 1205, Geneva, Switzerland

Corresponding author: Natasha Leclerc (natasha.leclerc@mail.utoronto.ca)

**Key Points:**

- Algal growth increments correlate most strongly with Atlantic Multidecadal Oscillation (AMO) but also with Arctic Oscillation (AO) trends.
- The algal record points to sea-ice reduction leading a positive AMO phase in the early to mid-1800s and Early Twentieth Century Warming.
- The algal proxy record from Lancaster Sound captures +AO-related sea-ice export into the Canadian Arctic Archipelago.

## Abstract

The Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), and related North Atlantic Oscillation (NAO) have been linked to multidecadal, decadal, and/or interannual sea-ice variability in the arctic, but their relative influences are still under evaluation. While instrumental AMO and reliable AO records are available since the mid-1800s and 1958, respectively, satellite sea-ice concentration datasets start only in 1979, limiting the shared timespan to study their interplay. Growth increments of the coralline algae, *Clathromorphum compactum*, can provide sea-ice proxy information for years prior to 1979. We present a seasonal 210-year algal record from Lancaster Sound in the Canadian Arctic Archipelago capturing low frequency AMO variability and high frequency interannual AO/NAO prior to 2000. We suggest that sea-ice variability here is strongly coupled to these large-scale climate processes, and that sea-ice cover was greater and the AO more negative in the early and late 19$^{th}$ century compared to the 20$^{th}$.

## Plain Language Summary

Arctic sea-ice variability is dually related to air/ocean temperatures and dynamic forces (wind patterns and ocean currents). While long-term basin-averaged temperature trends (i.e., Atlantic Multidecadal Oscillation) tend to influence variability over decades, cyclical wind patterns (e.g., Arctic Oscillation), may instead influence it seasonally and interannually. When the Atlantic Multidecadal and/or Arctic Oscillation (AMO/AO) are in a positive phase, warmer air and winds tend to export sea-ice out of the Arctic, and vice-versa during negative phases. Unfortunately, the span of the satellite sea-ice cover record is too short to study long-term sea-ice variability driven by these patterns. Therefore, proxy records are required to fill this gap. The tree-ring-like growth bands of an Arctic coralline red algae have produced multi-centennial proxy sea-ice cover records. We present a 210-year algal sea-ice proxy record, showing a relationship with instrumental AMO (1861 – present) and AO records (1958 – 2000). It also suggests that the AO was more negative and sea-ice cover was greater during the 19th century in comparison to the 20th century. Due to sea-ice's role in global climate at different timescales, this record can be utilized to tweak climate models or constrain the relative influence of internal forcing on sea-ice behaviour.

## 1 Introduction

Since the late 1970s, satellite imagery has made it possible to observe the rapid decline of arctic sea-ice, especially noticeable in the summer (perennial extent: (Nghiem et al., 2006); thickness: (Kwok & Rothrock, 2009); duration (Galley et al., 2016)). Warming caused by greenhouse gases (GHG) and other aerosol emissions, such as black carbon, are often cited as significant anthropogenic contributors to sea-ice decline (GHG: (Zhang & Walsh, 2006); aerosols Willis et al., 2018); black carbon: (Kim et al.,, 2005; Shindell & Faluvegi, 2009). Feedback mechanisms have also contributed to the warming trend, such as the ice-albedo feedback (Meier et al., 2014; Perovich et al., 2007), and the increasingly ice-free ocean surface promoting higher spring cloud coverage, trapping longwave radiation causing more ice melt (Francis & Hunter, 2006). Further, the respective natural variability of basin-wide oceanic temperatures and large-scale atmospheric patterns like the Atlantic Multidecadal Oscillation (AMO; a.k.a. Atlantic Multidecadal Variability), and the Arctic Oscillation (AO; a.k.a., Northern Annular Mode), and the related North Atlantic Oscillation (NAO), have also been shown to influence sea-ice variability (Divine & Dick, 2006; Miles et al., 2014; Rigor et al., 2002) and the recently observed decline in sea-ice conditions (Gillett et al., 2002; Rigor & Wallace, 2004; Rigor et al., 2002; Thompson & Wallace, 1998). Evidently, many factors control arctic sea-ice variability, yet the relative roles that natural and anthropogenetic forces play are still uncertain (Delworth et al., 2016). Further, reliable satellite sea-ice records are only available since the late 1970s and AO records prior to 1958 have many associated inconsistencies, challenging the ability to resolve how long-term natural climate patterns drive sea-ice variability.

In the absence of long instrumental records, tree-ring- or coral-based proxy records (Gray et al., 2004; Saenger et al., 2009), multi-proxy (terrestrial, ice core, lacustrine or coral archives: Mann et al., 1995) and modelled (Delworth & Mann, 2000) AMO records have attempted to clarify the periodicity of the AMO. Other studies have used historical and proxy records to study the interplay between AMO and sea-ice (Divine & Dick, 2006; Frankcombe et al., 2010; Macias-Fauria et al., 2010). Similar work has been accomplished with AO reconstructions which have also used the previously discussed archives (D'Arrigo et al., 2003; Rimbu et al., 2001; Rimbu et al., 2003; Sicre et al., 2014; Young et al., 2012), and deep-sea sediment cores (Darby, Ortiz, Grosch, & Lund, 2012). Important limitations of sediment cores are that they typically provide lower-temporal resolution records than tree-ring, coral, ice-core, and lake varve records, while the latter archives have been unable to directly capture oceanic or regional variability north of the tree line.

Alternatively, the annually-banded skeleton of the calcified coralline red algae species *Clathromorphum compactum* has been used to build direct oceanic proxy timeseries for arctic sea-ice changes and other environmental parameters (sea-ice: Halfar et al., 2013; Hetzinger et al., 2019; Leclerc et al., 2021, 2022; temperature variability: (Gamboa et al., 2010; Halfar et al., 2011; Halfar et al., 2008; Hetzinger et al., 2018; Hou et al., 2018; Williams et al., 2018, 2019); Suess effect: Hou et al., 2018; productivity: (Chan et al., 2017); runoff: (Hetzinger et al., 2021). This alga has a multi-century lifespan and inhabits shallow (typically <20 m depth) benthic niches with rocky substrate (Adey, 1966). *C. compactum* can archive variability of summer sea-ice cover since annual algal growth increment widths are heavily influenced by summer sunlight access for photosynthesis, which is diminished by overlying sea-ice cover (Williams et al., 2018). To date, several coralline-algal-sea-ice-proxy (CASIP) records have been produced from

*C. compactum* samples collected in the Arctic (Halfar et al., 2013; Hetzinger et al., 2019; Leclerc et al., 2022). In this study, we show that *C. compactum* growth increment records from Lancaster Sound in the Canadian Arctic Archipelago indicate a long-term relationship between sea-ice variability and summer AMO, AO and NAO indices.

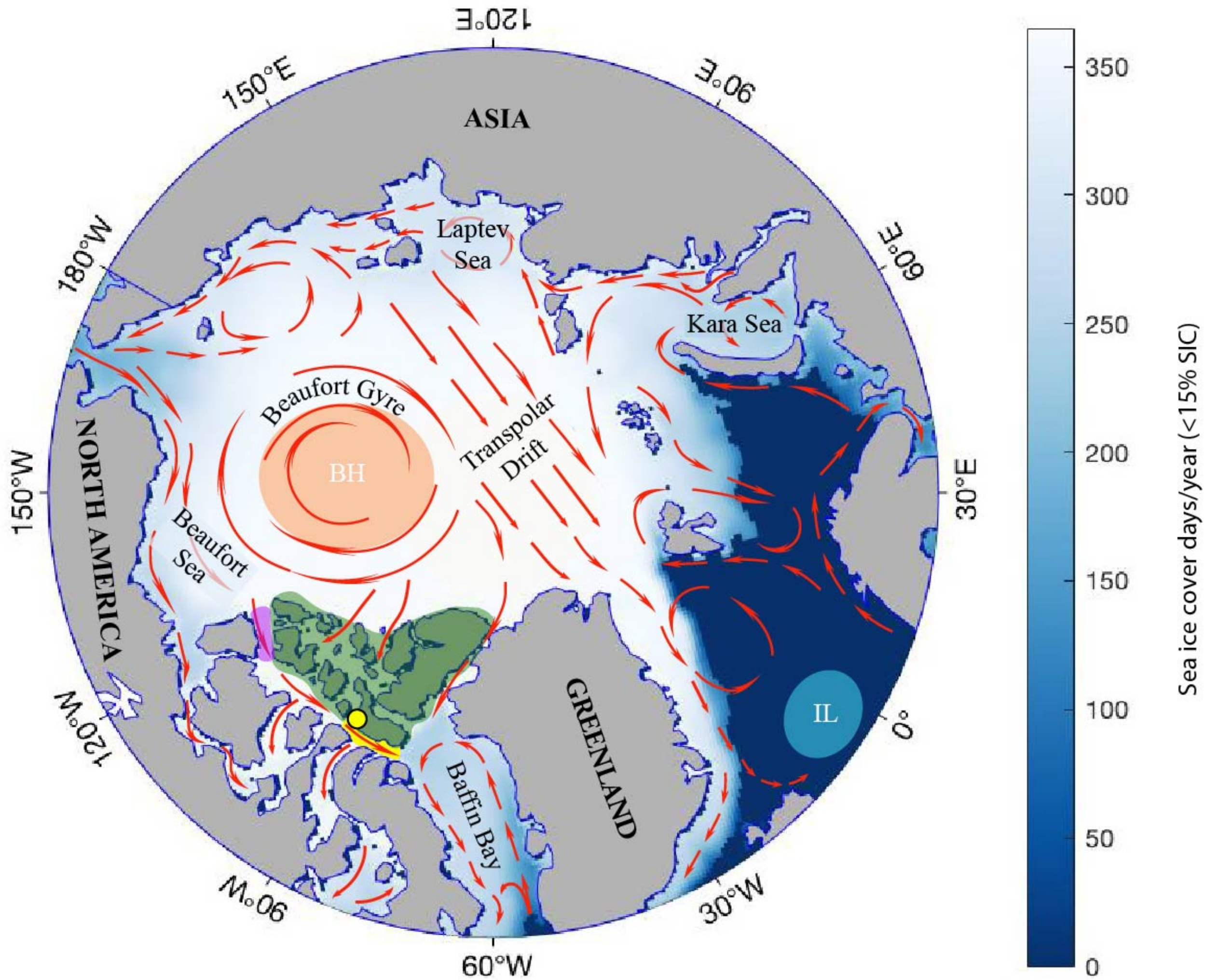


**Figure 1**. Representation of negative phase of Arctic Oscillation (AO) in the Arctic Ocean. Beaufort High (BH; orange); Icelandic Low (IL; light blue); Queen Elizabeth Islands (QEI: green); M'Clure Strait (purple); Beechey Island algal collection site (yellow dot); Lancaster Sound (yellow region). Negative AO phases promote a clockwise circulation of the Beaufort Gyre and are marked by a stronger BH sea level pressure that promotes a counter-clockwise gyre circulation and ice convergence. The opposite holds true for positive phases. Ocean circulation shown as red arrows (based on Fig. 3.29 in AMAP, 1998) and length of the ice-on season as white to dark blue gradient (1979-2015 mean days with >15% SIC: sourced from NSIDC (Meier et al., 2017).

## 2 Algal Data Preparation & Analysis Methods

Individual *Clathromorphum compactum* buildups were collected at 18-20 metre depths near Beechey Island, northwestern Lancaster Sound, Nunavut, Canada, via SCUBA in 2016 (74°42'54.46"N, 91°47'29.35"W; Fig. 1). Crusts were prepared into thick sections with an Isomet Precision Saw, ground and polished with a Struers Labopol polishing disk in 9 µm, 3 µm and 1 µm steps, with ultrasonic bath immersion between steps. Thick sections were then imaged with an Olympus VS-BX reflected light microscope paired to an automated stage. Images were stitched together with Geo.TS software and the 3 highest quality specimens (IDs: 2, 15 and 41) were selected for geochemical analysis (Fig. 2).

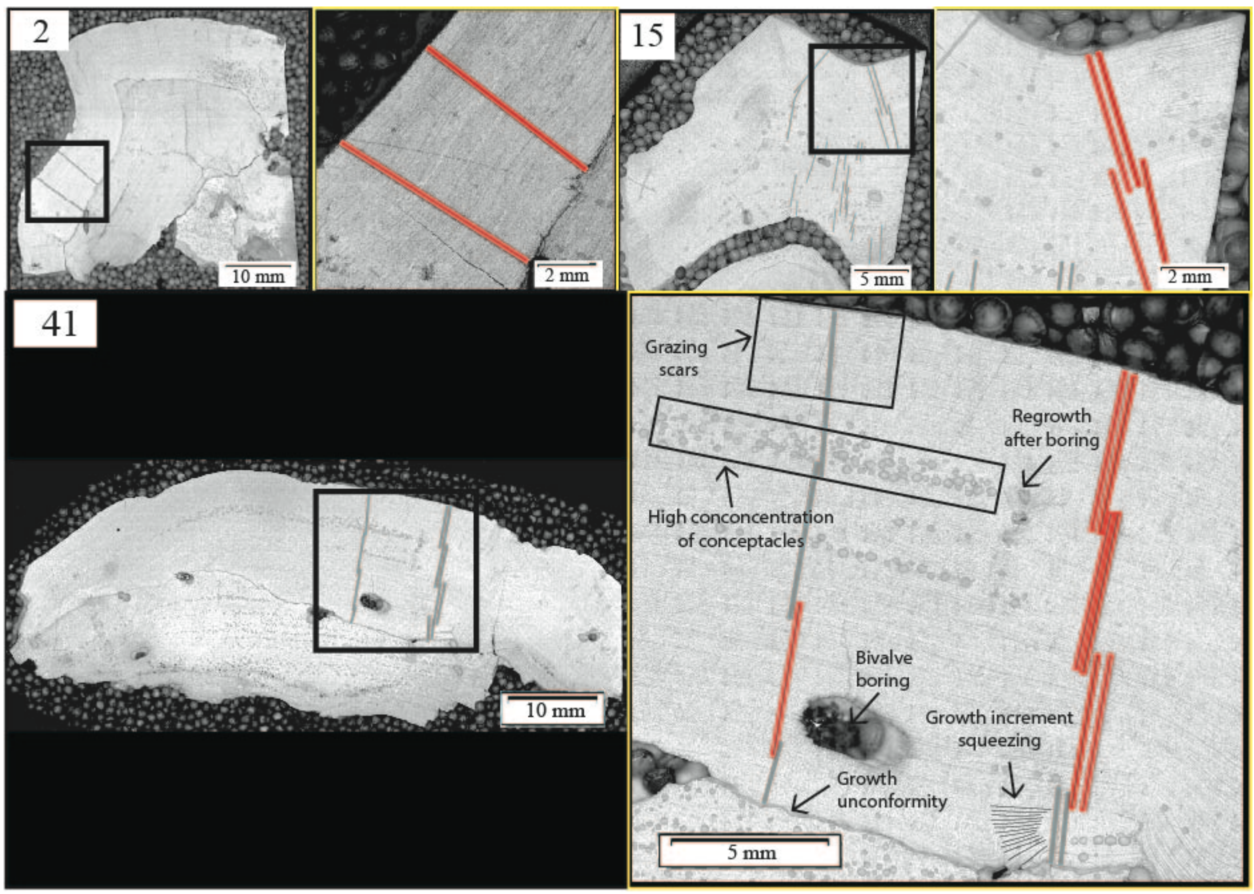


Figure 2. Overview (left) and magnified (right) images of *C. compactum* crusts from Beechey Island, Lancaster Sound. Laser ablation paths used along axis of growth indicated in red. Sample IDs shown in upper left corner, respectively.

Geochemical data were obtained at the University of Toronto's Earth Science Center with a NWR 193 UC laser ablation inductively coupled mass spectrometry (LA-ICP-MS) system linked to an Agilent 7900 quadrupole mass spectrometer. Line scans were ablated at a speed of 5 µm/second along the growth axis, using an aperture size of 10 × 70 µm, and a 10 Hz laser pulse rate (*see details in* Hetzinger et al., 2011). By comparing growth increments visible on microscope images with the widths of annual Mg/Ca cycles calculated from LA-ICP-MS data, age models and growth increment width timeseries were built and crossdated between 2 transects for intra-sample replicability and between 3 samples to ensure adequate inter-specimen coherence (for detailed procedures see Leclerc et al., 2022). Prior to 1880, only sample 41 (3 crossdated transects), which provided the longest continuous chronology, was used to extend the record back to 1805. All data was normalized and averaged across crossdated measurements to form a master chronology.

## 3 Instrumental Data & Statistics

Correlation analysis (linear regression) was used to determine the relationship between the algal record and instrumental indices. Monthly AO index values based on instrumental sea level pressure (SLP: Poleward of 20°N calculated by projecting the AO pattern on SLP anomalies) computed through the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Wallace & Thompson, 2000). Monthly Hurrell North Atlantic Oscillation (NAO) index values are based on principal component analysis of SLP over the Atlantic. While the instrumental AO index goes as far back as 1899, early data issues include different SLP sources for different time periods, with discontinuities identified between data source transitions (Trenberth & Paolino, 1980). Therefore, only later instrumental AO index values (1958-2015) were used in this study due to confidence issues with early data points. Further, the NAO record was shortened to match the length of the AO record for even comparison to the algal record in Table 1. The correlation between the CASIP record and the full length NAO record is reported and plotted in Figure 4. Monthly AMO index values are the 10-year running mean values smoothed from the Kaplan SST V2 timeseries. Seasonal means were calculated by averaging summer months (May-Oct). Spatial correlation analysis and linear regression to monthly NSIDC sea-ice concentration dataset see procedure in (Leclerc et al., 2021) was computed using Matlab and m_map mapping toolbox. The software kSpectra is an implementation of techniques described in Ghil et al. (2002) and was used to run multi-taper and singular spectral analyses (SSA) on instrumental and proxy datasets to determine if the algal record shared AO, NAO and AMO frequency signatures.

## 4 Results & Discussion

Since higher sea-ice cover, in typically colder years, limits growth, we expected a negative correlation between regional sea-ice cover and annual growth, and positive correlations with AO, NAO, and AMO. Accordingly, spatial correlation analysis shows strongly significant negative correlations ($p<0.001$) between Beechey Island growth increment chronology and regional satellite sea-ice concentrations (Fig. 3). Highly significant spatial relationships also centered along the northern coast of the Canadian Arctic Archipelago, the Beaufort Sea and the Laptev Sea (Fig. 3a). At a more localized scale, the algal growth increment timeseries correlates significantly ($R = -0.71$; $p<0.001$) with satellite sea-ice concentrations (Leclerc et al., 2022) (Fig. 3b). The confirmation of the local sea-ice–algal growth relationship suggests that if AMO, AO or NAO and sea-ice are related in Lancaster Sound, the algal timeseries should record their signal. Indeed, correlation analysis demonstrated that the master Beechey Island chronology significantly ($p<0.001$) captured the decadally-smoothed AMO index (Tab. 1). The AO was also significantly correlated at annual ($p<0.01$) and decadal ($p<0.05$) resolutions, and the NAO correlation was markedly strong at a decadal resolution ($p<0.001$), however only until 2000.

The lack of correlation between AO and sea-ice cover in recent decades has previously been documented (Feldstein, 2002; Overland & Wang, 2005; Overland & Wang, 2010; Stroeve et al.,

2011) and this coralline algal record supports it as well. Its manifestation in the Canadian Arctic Archipelago (CAA) may also be related to recent shifts in the duration of ice bridges, landfast ice between landmasses which form in winter and block sea-ice export until summer collapse. When ice bridges at M'Clure Strait or the Queen Elizabeth Islands (QEI) (Fig. 1) collapse, sea-ice from the Arctic Ocean is free to be imported into the CAA, especially during positive AO phases (Howell et al., 2013). Contrary to the +AO-stimulated ice breakup/export acceleration, +AO-stimulated sea-ice import after ice bridge collapse may limit algal light access and mute the AO signal. In fact, since 2005 there has been an increase of ice inflow into the CAA through the Queen Elizabeth Islands, which tends to flow south towards Lancaster Sound (Howell et al., 2013). Other data from the Nares Strait suggest that ice volume export through the Strait has increased recently in comparison to the 1997-2009 mean, linked to the trend of shorter duration of ice bridges (Moore et al., 2021). This may be responsible for the masked AO signal in the Beechey Island CASIP record since the turn of the millennium (Supplentary Figure 1; Tab. 1).

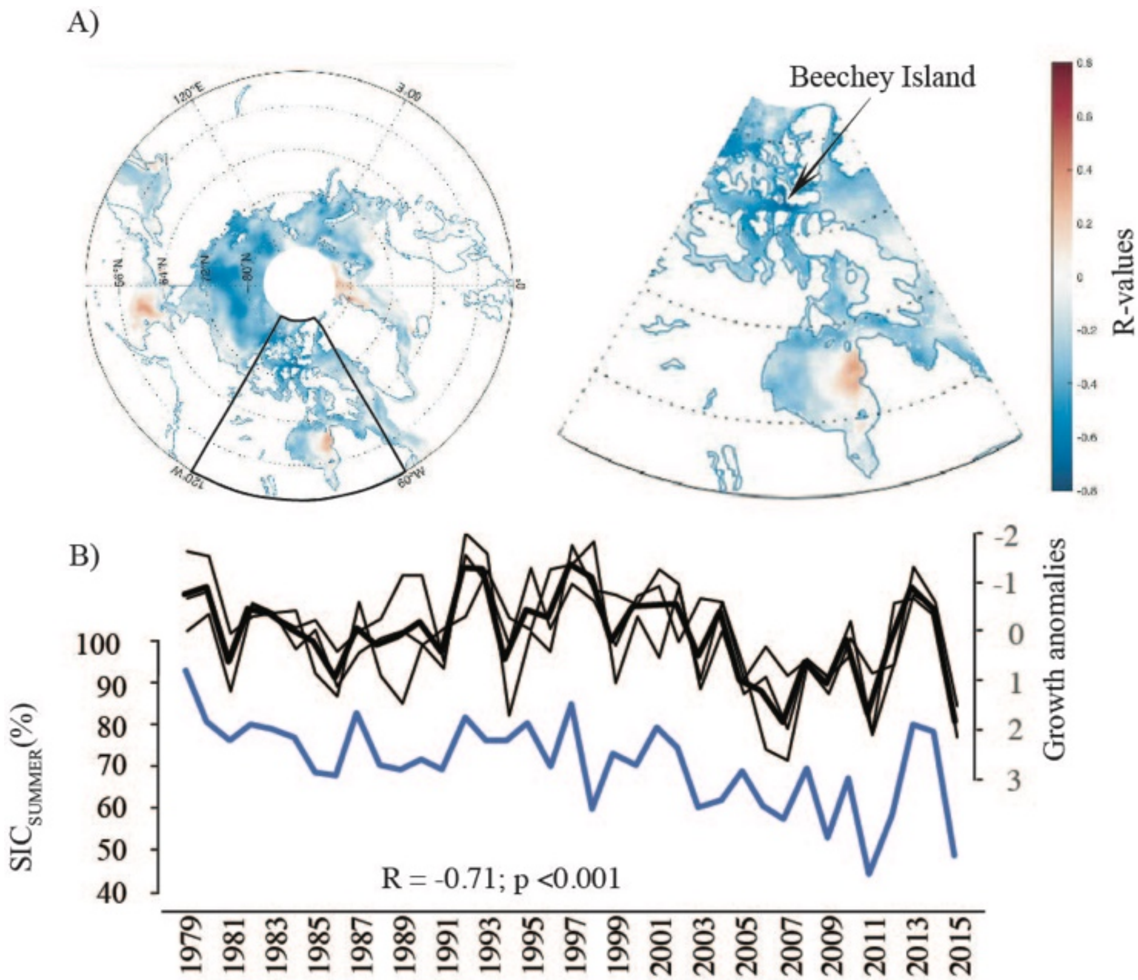


**Figure 3.** A) Spatial correlation analysis between gridded Arctic SIC and Beechey Island growth increment chronology. Right plot shows Beechey Island region enlarged. B) Plotted algal growth increment timeseries (black: anomalies = (annual value – average) / standard deviation) and NSIDC sea-ice concentrations (blue: 75 km$^2$ around Beechey Island site) (see Leclerc et al.,

2022 for original figure of subplot B). Note that growth anomalies are plotted inversely. R-value indicates strength of correlation.

Periods with larger growth increments coincide with a strongly positive AMO period and the Early Twentieth Century Warming (ETCW: 1920s-1950s) period (Fig. 4). The ETCW has been shown to be associated with sea-ice retreat in the Barents Sea caused by stronger westerly winds between Spitsbergen and Norway (Bengtsson et al., 2004), and has also been recorded by *C. compactum* Ba/Ca and growth-Mg/Ca anomaly timeseries from Spitsbergen (Hetzinger et al., 2021, 2019). Day et al. (2012) suggested the recent positive phase of AMO could explain 5-30% of satellite summer sea-ice loss and Miles et al. (2014) suggested AMO was a major driver of sea-ice variability from the past 800 years to the 1990s. Similarly, our data showed that the AMO and ETCW affected ice decline in Lancaster Sound in the mid-20$^{th}$ century. Multi-taper spectral analysis results showed multidecadal variability in the algal chronology (significant at 99% level, 60-77-year signal, CASIP: 1805–2015; Supplementary Figure S1), comparable to the posited periodicity of AMO (60–80 years) (Kerr, 2000; Schlesinger & Ramankutty, 1994). Significant (95% level) interannual signals (at 2 and 3 years) were also found, closely matching AO signatures (Supplementary Figure S1) previously shown to affect sea-ice circulation in the Baltic Sea (Jevrejeva et al., 2003). However, the CASIP multi-taper results did not capture AO's decadal variability as reported elsewhere (Ramos da Silva & Avissar, 2005). However, singular spectrum analysis (SSA) of the shortened CASIP record (1960-2000) identified significant variability at 7.6–10.3 years responsible for more than 60% of variance (Suplementary Figure S1). In the $AO_{SUMMER}$ record (1960-2000), most of the variability is interannual (2.5-5.1 years; details in Supplementary Text S1), a decadal signal (10.6-year) is explaining only 16.9% of total variance. In summary, multi-taper and SSA did not fully identify the 8 – 10-year AO signals previously identified through wavelet power spectrum analysis (Ramos da Silva & Avissar, 2005). This further suggests that the shared variability at the approximately 2–3-year periodicity level is what the sea-ice-AO and sea-ice-CASIP relationships are recording in the CAA.

The part of the algal record that extends earlier than the instrumental NAO record (i.e., prior to 1899), suggests colder and heavier ice conditions in the 19$^{th}$ century in comparison to the 20$^{th}$ century similar to the findings of indirect (temperature) sea-ice proxy tree ring records (D'Arrigo et al., 2003; Young et al., 2012). The algal chronology also suggests a period of less ice in the mid-1800s possibly due to more positive AO/NAO or AMO, or both (Fig. 4). While, many have suggested that the Little Ice Age and colder conditions persisted until the late 1800s, this slightly warmer period in the mid-1800s is supported by multiple Arctic proxy records that find episodic warming at this time (Jennings & Weiner, 1996; Massé et al., 2008: records synthecized in Miles et al., 2020). This warming period is also corroborated by ice cap stratigraphy from nearby Devon Island, Greenland ice sheets and marine cores from the Labrador Sea, which suggested early warming in 1860s and a more intense warming trend beginning around 1890 (Keigwin et al., 2003; Koerner, 1977; Trusel et al., 2018). The mid-1800s mild warming period found in our record predates those found in other AMO proxy records from terrestrial archives (e.g., Gray et al., 2004), which shows a later warming period later in the 1800s, and cooler 1830s-1840s (Fig. 4). While, some suggest some uncertainty in terrestrial AMO records (e.g., Miles et al., 2020), it is notable that sea-ice and NAO trends have been shown to lead AMO variability in some regions, and that the timing in AMO peaks and troughs are regionally variable (Alexander et al., 2014; Peterson et al., 2015). As the NAO and AO are highly correlated (Rigor et al., 2002), this could also apply to AO precursers to AMO.

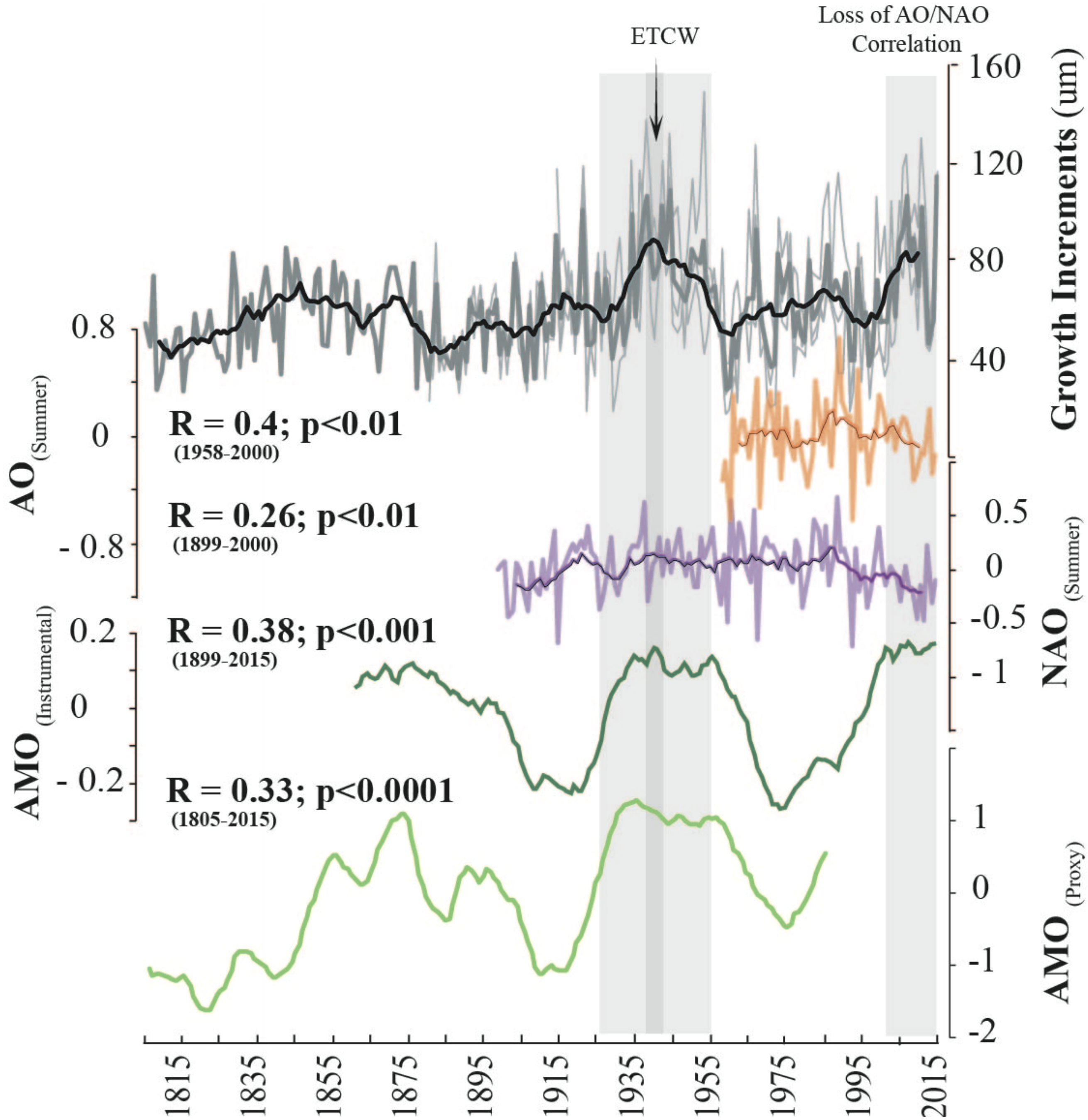


**Figure 4.** Relationship between crossdated Beechey Island growth increment (i.e., CASIP) detrended chronology and detrended AO (orange), NAO (purple) and AMO (dark green) climate indices for summer months (May-October). Individual algal samples (light grey); average of all algal samples (dark grey); 10-yr running mean of average growth, AO and NAO (black, dark orange, and dark purple lines, respectively). Tree ring-based proxy AMO timeseries (light green) from Gray et al. (2004). AMO is 10-year averaged index (no 10-yr running mean). Early

Twentieth Century Warming (ETCW: 1920-1960) and loss of correlation in 2000s periods (grey bars), and major El Niño event (arrow: 1939-1942).

Algal-sea-ice-proxy (CASIP) records are indicators of a combination of sea-ice variables affecting light penetration to the benthos: present/absent ice cover (related to melt/freeze up and wind and current dynamics), seasonal duration of cover, thickness and snow cover. Together, the AMO, AO, and NAO have the capacity of affecting all these variables. Samelson et al. (2006) suggested that the formation of land-fast ice in the CAA is controlled by both winds and air temperature, both are parameters influenced by these large atmospheric and ocean temperature patterns. Furthermore, Peterson et al. (2012) found that monthly longshore wind anomalies in the Beaufort Sea, which are heavily influenced by AO, stimulated 43% of Lancaster Sound's volume transport anomaly variance. This is supported by the significant relationship between the Beechey Island CASIP record and gridded sea-ice concentrations on the exterior CAA coast bordering the Beaufort Sea (Fig. 2a). The linked variability and coupling of the AO/NAO and AMO are posited to stem in part from interannual and long-term sea-ice cover trends and/or stimulation of Atlantic Meriodinal Overturning Circulation (AMOC) (Medhaug et al., 2012; Peterson et al., 2015; Polyakov et al., 2010; Polyakov et al., 2005; Yang et al., 2016). Our results seem to support the assertion of arctic sea-ice's important role in AMO variability.

**Table 1.** Linear regression (R- and p-values) correlations of Beechey Island algal growth record to climate indices at seasonal (summer) and decadal (10-year running means of summer values) resolutions. Highlighted grey boxes are significant positive correlations ($p<0.5$; darkest shades indicate $p<0.01$).

| **AO (May-Oct: 1958 -)** | | **NAO (May-Oct: 1958 -)** | | **AMO (Annual: 1861 -)** |
|---|---|---|---|---|
| **Seasonal** | **Decadal** | **Seasonal** | **Decadal** | **Decadal** |
| **Anomalies (- 2015)** | | | | |
| 0.23<br>p=0.08 | -0.11<br>p=0.4 | 0.05<br>p=0.7 | -0.49<br>p<0.001 | 0.31<br>p= 0.001 |
| **Anomalies (- 2000)** | | | | |
| 0.41<br>p<0.01 | 0.41<br>p<0.01 | 0.33<br>p=0.03 | 0.53<br>p<0.001 | 0.21<br>p= 0.01 |
| **Detrended (- 2015)** | | | | |
| 0.17<br>p=0.2 | -0.37<br>p<0.01 | 0.08<br>p=0.55 | -0.4<br>p<0.01 | 0.39<br>p<0.001 |
| **Detrended (- 2000)** | | | | |
| 0.4<br>p<0.01 | 0.31<br>p<0.05 | 0.34<br>p<0.05 | 0.64<br>p<0.001 | 0.38<br>p<0.001 |
| Note. All negative correlations are considered insignificant. | | | | |

## 5 Summary & Conclusion

The *C. compactum* growth increment chronology from Beechey Island recorded: 1) lower sea-ice cover during the 1800s in comparison to the 1900s; 2) slightly lighter sea-ice years in the mid-1800s; 3) the Earth Twentieth Century Warming period; 4) significant sea-ice response to AMO throughout the record; 5) significant sea-ice responses to AO/NAO from 1960-2000, and; 6) lack of sea-ice response to AO/NAO from 2000-2015 possibly due to external factors such as the greenhouse gas (GHG) effect and ice-albedo feedbacks. The development of longer high-resolution proxy records such as CASIP timeseries is critical to understanding the role of cryospheric-atmospheric feedbacks in the many intertwined components in the global climate system (Gao et al., 2015). The Canadian Arctic Archipelago, which tends to trap multi-year ice (Howell et al., 2008; Kwok, 2015), makes up a significant part of the *Last Ice Area*, predicted to be the last arctic region to experience summer ice cover (Moore et al., 2019). As this area will become increasingly crucial in the coming years, and potentially more hazardous to naval travel (Howell et al., 2022), *C. compactum* CASIP records can provide important historical and pre-industrial baselines. While it is reasonably well understood that atmospheric patterns have an effect on sea-ice extent, the interplay between coastal sea-ice cover and atmospheric patterns, especially in the CAA is still not well understood. Here we find strong links between internal variability and sea-ice trends. However, we note that these links are muted in recent decades (especially after 2000) due to anthropogenic forcing and possibly enhancement of ice penetration through QEI gates in the Canadian Arctic Archipelago (Howell et al., 2023).

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**Open Research**

This article contains original data (algal chronologies 1805-1870) and previously published data (algal chronologies 1871-2015) which is available in (Leclerc et al., 2022). Original data extend the previously published record. All coralline red algae data sets have been submitted to the NOAA National Centers for Environmental Information Paleoclimatology Data Repository (*awaiting official doi*). Primary data sets for this research are also included in figures and Supporting Information S1 files. Environmental data sets include: The monthly AO Index values were extracted from KMNI Climate Explorer (based on Trenberth & Paolino, 1980). Monthly Hurrell North Atlantic Oscillation (NAO) index values were extracted from NCAR Climate Data Guide (https://climatedataguide.ucar.edu/). Monthly AMO 10-year running mean values smoothed from the Kaplan SST V2 were extracted from NOAA PSL1 (http://www.psl.noaa.gov/data/timeseries/AMO/). Spatial correlation analysis and linear regression to monthly NSIDC sea-ice concentration dataset (Version 3: https://nsidc.org/data/g02202; Peng et al., 2013; Meier et al., 2017; see procedure in (Leclerc et al., 2021) was computed using Matlab and m_map mapping toolbox. The software kSpectra described in Ghil et al. (2002) was used to run multi-taper and singular spectral analyses.

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# Growth increments of coralline red alga *Clathromorphum compactum* capture sea-ice variability links to Atlantic Multidecadal and Arctic Oscillations (1805 – 2015)

**N. Leclerc[1,2], J. Halfar[1], S. Hetzinger[3], A. Tsay[4], and G. W. K. Moore[1]**

[1] Chemical and Physical Sciences Department, University of Toronto Mississauga, 3359 Mississauga Road N., Ontario, L5L 1C6, Canada

[2] Department of Archaeology, Memorial University of Newfoundland, 210 Prince Philip Dr., Newfoundland & Labrador, A1C 5S7

[3] Christian-Albrechts-Universität zu Kiel, Institut für Geowissenschaften, Ludewig-Meyn-Str. 10, 24118 Kiel, Germany

[4] Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, 1205, Geneva, Switzerland

Corresponding author: Natasha Leclerc (natasha.leclerc@mail.utoronto.ca)

**Key Points:**

- Algal growth increments correlate most strongly with Atlantic Multidecadal Oscillation (AMO) but also with Arctic Oscillation (AO) trends.
- The algal record points to sea-ice reduction leading a positive AMO phase in the early to mid-1800s and Early Twentieth Century Warming.
- The algal proxy record from Lancaster Sound captures +AO-related sea-ice export into the Canadian Arctic Archipelago.

## Abstract

The Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), and related North Atlantic Oscillation (NAO) have been linked to multidecadal, decadal, and/or interannual sea-ice variability in the arctic, but their relative influences are still under evaluation. While instrumental AMO and reliable AO records are available since the mid-1800s and 1958, respectively, satellite sea-ice concentration datasets start only in 1979, limiting the shared timespan to study their interplay. Growth increments of the coralline algae, *Clathromorphum compactum*, can provide sea-ice proxy information for years prior to 1979. We present a seasonal 210-year algal record from Lancaster Sound in the Canadian Arctic Archipelago capturing low frequency AMO variability and high frequency interannual AO/NAO prior to 2000. We suggest that sea-ice variability here is strongly coupled to these large-scale climate processes, and that sea-ice cover was greater and the AO more negative in the early and late 19$^{th}$ century compared to the 20$^{th}$.



## Plain Language Summary

Arctic sea-ice variability is dually related to air/ocean temperatures and dynamic forces (wind patterns and ocean currents). While long-term basin-averaged temperature trends (i.e., Atlantic Multidecadal Oscillation) tend to influence variability over decades, cyclical wind patterns (e.g., Arctic Oscillation), may instead influence it seasonally and interannually. When the Atlantic Multidecadal and/or Arctic Oscillation (AMO/AO) are in a positive phase, warmer air and winds tend to export sea-ice out of the Arctic, and vice-versa during negative phases. Unfortunately, the span of the satellite sea-ice cover record is too short to study long-term sea-ice variability driven by these patterns. Therefore, proxy records are required to fill this gap. The tree-ring-like growth bands of an Arctic coralline red algae have produced multi-centennial proxy sea-ice cover records. We present a 210-year algal sea-ice proxy record, showing a relationship with instrumental AMO (1861 – present) and AO records (1958 – 2000). It also suggests that the AO was more negative and sea-ice cover was greater during the 19th century in comparison to the 20th century. Due to sea-ice's role in global climate at different timescales, this record can be utilized to tweak climate models or constrain the relative influence of internal forcing on sea-ice behaviour.

## 1 Introduction

Since the late 1970s, satellite imagery has made it possible to observe the rapid decline of arctic sea-ice, especially noticeable in the summer (perennial extent: (Nghiem et al., 2006); thickness: (Kwok & Rothrock, 2009); duration (Galley et al., 2016)). Warming caused by greenhouse gases (GHG) and other aerosol emissions, such as black carbon, are often cited as significant anthropogenic contributors to sea-ice decline (GHG: (Zhang & Walsh, 2006); aerosols Willis et al., 2018); black carbon: (Kim et al.,, 2005; Shindell & Faluvegi, 2009). Feedback mechanisms have also contributed to the warming trend, such as the ice-albedo feedback (Meier et al., 2014; Perovich et al., 2007), and the increasingly ice-free ocean surface promoting higher spring cloud coverage, trapping longwave radiation causing more ice melt (Francis & Hunter, 2006). Further, the respective natural variability of basin-wide oceanic temperatures and large-scale atmospheric patterns like the Atlantic Multidecadal Oscillation (AMO; a.k.a. Atlantic Multidecadal Variability), and the Arctic Oscillation (AO; a.k.a., Northern Annular Mode), and the related North Atlantic Oscillation (NAO), have also been shown to influence sea-ice variability (Divine & Dick, 2006; Miles et al., 2014; Rigor et al., 2002) and the recently observed decline in sea-ice conditions (Gillett et al., 2002; Rigor & Wallace, 2004; Rigor et al., 2002; Thompson & Wallace, 1998). Evidently, many factors control arctic sea-ice variability, yet the relative roles that natural and anthropogenetic forces play are still uncertain (Delworth et al., 2016). Further, reliable satellite sea-ice records are only available since the late 1970s and AO records prior to 1958 have many associated inconsistencies, challenging the ability to resolve how long-term natural climate patterns drive sea-ice variability.

In the absence of long instrumental records, tree-ring- or coral-based proxy records (Gray et al., 2004; Saenger et al., 2009), multi-proxy (terrestrial, ice core, lacustrine or coral archives: Mann et al., 1995) and modelled (Delworth & Mann, 2000) AMO records have attempted to clarify the periodicity of the AMO. Other studies have used historical and proxy records to study the interplay between AMO and sea-ice (Divine & Dick, 2006; Frankcombe et al., 2010; Macias-Fauria et al., 2010). Similar work has been accomplished with AO reconstructions which have also used the previously discussed archives (D'Arrigo et al., 2003; Rimbu et al., 2001; Rimbu et al., 2003; Sicre et al., 2014; Young et al., 2012), and deep-sea sediment cores (Darby, Ortiz, Grosch, & Lund, 2012). Important limitations of sediment cores are that they typically provide lower-temporal resolution records than tree-ring, coral, ice-core, and lake varve records, while the latter archives have been unable to directly capture oceanic or regional variability north of the tree line.

Alternatively, the annually-banded skeleton of the calcified coralline red algae species *Clathromorphum compactum* has been used to build direct oceanic proxy timeseries for arctic sea-ice changes and other environmental parameters (sea-ice: Halfar et al., 2013; Hetzinger et al., 2019; Leclerc et al., 2021, 2022; temperature variability: (Gamboa et al., 2010; Halfar et al., 2011; Halfar et al., 2008; Hetzinger et al., 2018; Hou et al., 2018; Williams et al., 2018, 2019); Suess effect: Hou et al., 2018; productivity: (Chan et al., 2017); runoff: (Hetzinger et al., 2021). This alga has a multi-century lifespan and inhabits shallow (typically <20 m depth) benthic niches with rocky substrate (Adey, 1966). *C. compactum* can archive variability of summer sea-ice cover since annual algal growth increment widths are heavily influenced by summer sunlight access for photosynthesis, which is diminished by overlying sea-ice cover (Williams et al., 2018). To date, several coralline-algal-sea-ice-proxy (CASIP) records have been produced from

*C. compactum* samples collected in the Arctic (Halfar et al., 2013; Hetzinger et al., 2019; Leclerc et al., 2022). In this study, we show that *C. compactum* growth increment records from Lancaster Sound in the Canadian Arctic Archipelago indicate a long-term relationship between sea-ice variability and summer AMO, AO and NAO indices.

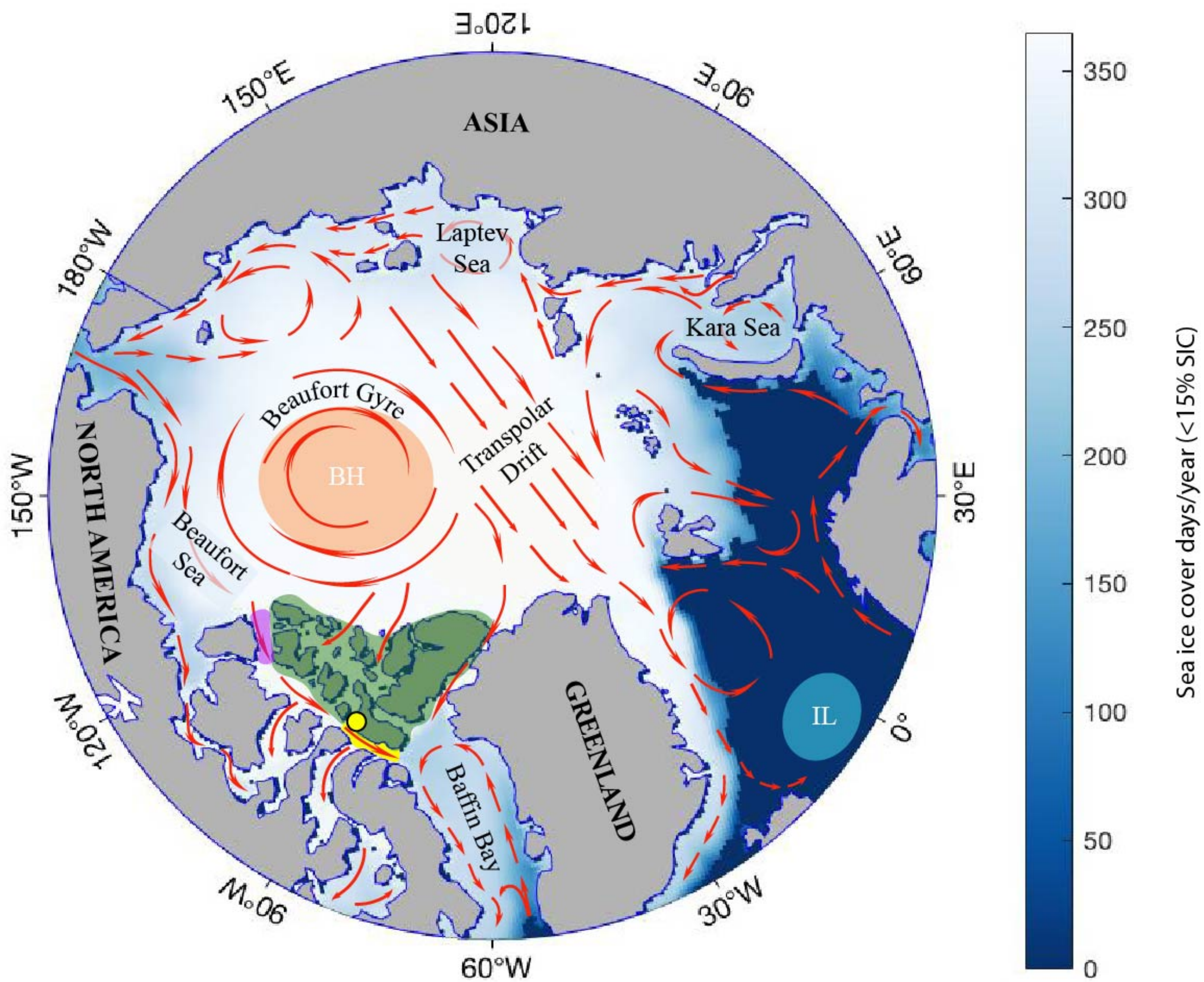


**Figure 1**. Representation of negative phase of Arctic Oscillation (AO) in the Arctic Ocean. Beaufort High (BH; orange); Icelandic Low (IL; light blue); Queen Elizabeth Islands (QEI: green); M'Clure Strait (purple); Beechey Island algal collection site (yellow dot); Lancaster Sound (yellow region). Negative AO phases promote a clockwise circulation of the Beaufort Gyre and are marked by a stronger BH sea level pressure that promotes a counter-clockwise gyre circulation and ice convergence. The opposite holds true for positive phases. Ocean circulation shown as red arrows (based on Fig. 3.29 in AMAP, 1998) and length of the ice-on season as white to dark blue gradient (1979-2015 mean days with >15% SIC: sourced from NSIDC (Meier et al., 2017).

## 2 Algal Data Preparation & Analysis Methods

Individual *Clathromorphum compactum* buildups were collected at 18-20 metre depths near Beechey Island, northwestern Lancaster Sound, Nunavut, Canada, via SCUBA in 2016 (74°42'54.46"N, 91°47'29.35"W; Fig. 1). Crusts were prepared into thick sections with an Isomet Precision Saw, ground and polished with a Struers Labopol polishing disk in 9 µm, 3 µm and 1 µm steps, with ultrasonic bath immersion between steps. Thick sections were then imaged with an Olympus VS-BX reflected light microscope paired to an automated stage. Images were stitched together with Geo.TS software and the 3 highest quality specimens (IDs: 2, 15 and 41) were selected for geochemical analysis (Fig. 2).

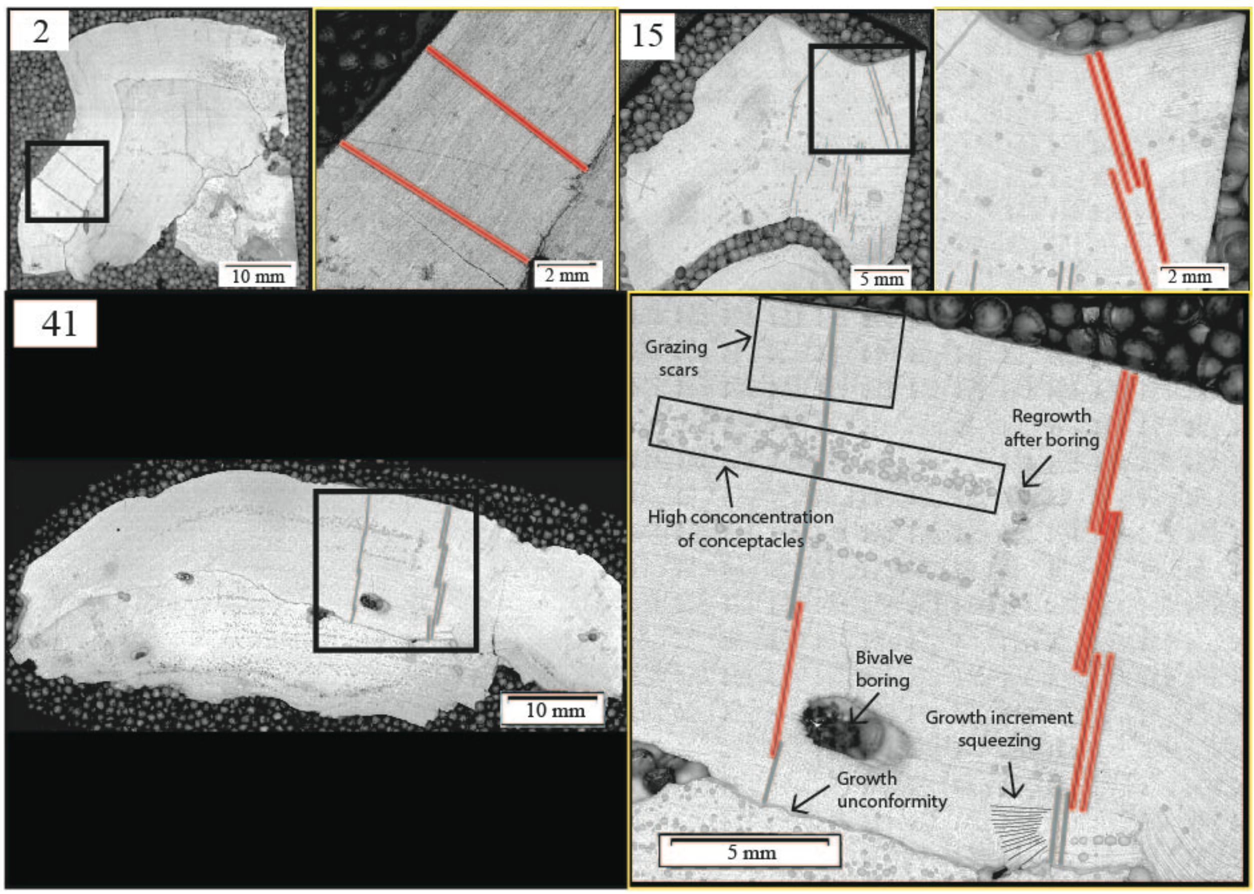


Figure 2. Overview (left) and magnified (right) images of *C. compactum* crusts from Beechey Island, Lancaster Sound. Laser ablation paths used along axis of growth indicated in red. Sample IDs shown in upper left corner, respectively.

Geochemical data were obtained at the University of Toronto's Earth Science Center with a NWR 193 UC laser ablation inductively coupled mass spectrometry (LA-ICP-MS) system linked to an Agilent 7900 quadrupole mass spectrometer. Line scans were ablated at a speed of 5 µm/second along the growth axis, using an aperture size of 10 × 70 µm, and a 10 Hz laser pulse rate (*see details in* Hetzinger et al., 2011). By comparing growth increments visible on microscope images with the widths of annual Mg/Ca cycles calculated from LA-ICP-MS data, age models and growth increment width timeseries were built and crossdated between 2 transects for intra-sample replicability and between 3 samples to ensure adequate inter-specimen coherence (for detailed procedures see Leclerc et al., 2022). Prior to 1880, only sample 41 (3 crossdated transects), which provided the longest continuous chronology, was used to extend the record back to 1805. All data was normalized and averaged across crossdated measurements to form a master chronology.

## 3 Instrumental Data & Statistics

Correlation analysis (linear regression) was used to determine the relationship between the algal record and instrumental indices. Monthly AO index values based on instrumental sea level pressure (SLP: Poleward of 20°N calculated by projecting the AO pattern on SLP anomalies) computed through the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Wallace & Thompson, 2000). Monthly Hurrell North Atlantic Oscillation (NAO) index values are based on principal component analysis of SLP over the Atlantic. While the instrumental AO index goes as far back as 1899, early data issues include different SLP sources for different time periods, with discontinuities identified between data source transitions (Trenberth & Paolino, 1980). Therefore, only later instrumental AO index values (1958-2015) were used in this study due to confidence issues with early data points. Further, the NAO record was shortened to match the length of the AO record for even comparison to the algal record in Table 1. The correlation between the CASIP record and the full length NAO record is reported and plotted in Figure 4. Monthly AMO index values are the 10-year running mean values smoothed from the Kaplan SST V2 timeseries. Seasonal means were calculated by averaging summer months (May-Oct). Spatial correlation analysis and linear regression to monthly NSIDC sea-ice concentration dataset see procedure in (Leclerc et al., 2021) was computed using Matlab and m_map mapping toolbox. The software kSpectra is an implementation of techniques described in Ghil et al. (2002) and was used to run multi-taper and singular spectral analyses (SSA) on instrumental and proxy datasets to determine if the algal record shared AO, NAO and AMO frequency signatures.

## 4 Results & Discussion

Since higher sea-ice cover, in typically colder years, limits growth, we expected a negative correlation between regional sea-ice cover and annual growth, and positive correlations with AO, NAO, and AMO. Accordingly, spatial correlation analysis shows strongly significant negative correlations ($p<0.001$) between Beechey Island growth increment chronology and regional satellite sea-ice concentrations (Fig. 3). Highly significant spatial relationships also centered along the northern coast of the Canadian Arctic Archipelago, the Beaufort Sea and the Laptev Sea (Fig. 3a). At a more localized scale, the algal growth increment timeseries correlates significantly ($R = -0.71$; $p<0.001$) with satellite sea-ice concentrations (Leclerc et al., 2022) (Fig. 3b). The confirmation of the local sea-ice–algal growth relationship suggests that if AMO, AO or NAO and sea-ice are related in Lancaster Sound, the algal timeseries should record their signal. Indeed, correlation analysis demonstrated that the master Beechey Island chronology significantly ($p<0.001$) captured the decadally-smoothed AMO index (Tab. 1). The AO was also significantly correlated at annual ($p<0.01$) and decadal ($p<0.05$) resolutions, and the NAO correlation was markedly strong at a decadal resolution ($p<0.001$), however only until 2000.

The lack of correlation between AO and sea-ice cover in recent decades has previously been documented (Feldstein, 2002; Overland & Wang, 2005; Overland & Wang, 2010; Stroeve et al.,

2011) and this coralline algal record supports it as well. Its manifestation in the Canadian Arctic Archipelago (CAA) may also be related to recent shifts in the duration of ice bridges, landfast ice between landmasses which form in winter and block sea-ice export until summer collapse. When ice bridges at M'Clure Strait or the Queen Elizabeth Islands (QEI) (Fig. 1) collapse, sea-ice from the Arctic Ocean is free to be imported into the CAA, especially during positive AO phases (Howell et al., 2013). Contrary to the +AO-stimulated ice breakup/export acceleration, +AO-stimulated sea-ice import after ice bridge collapse may limit algal light access and mute the AO signal. In fact, since 2005 there has been an increase of ice inflow into the CAA through the Queen Elizabeth Islands, which tends to flow south towards Lancaster Sound (Howell et al., 2013). Other data from the Nares Strait suggest that ice volume export through the Strait has increased recently in comparison to the 1997-2009 mean, linked to the trend of shorter duration of ice bridges (Moore et al., 2021). This may be responsible for the masked AO signal in the Beechey Island CASIP record since the turn of the millennium (Supplentary Figure 1; Tab. 1).

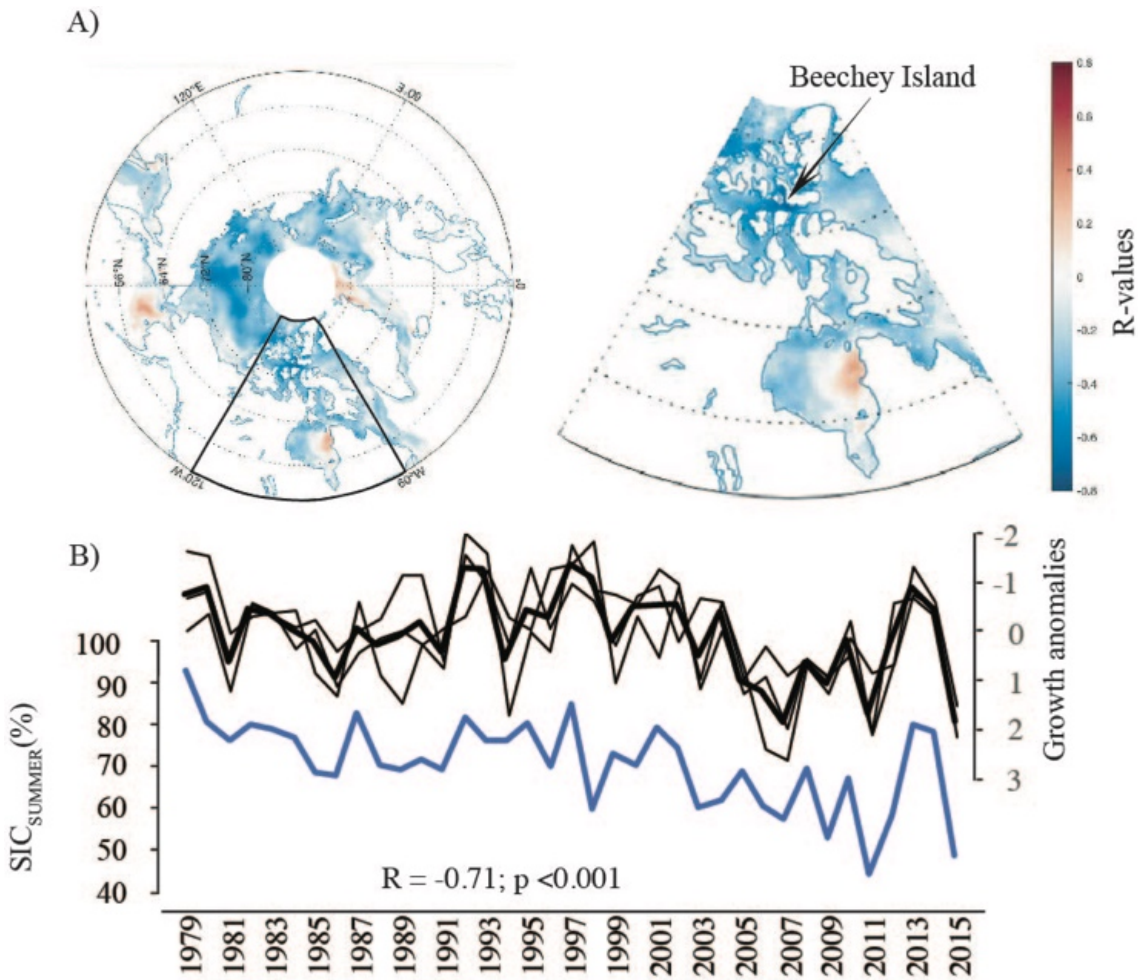


**Figure 3.** A) Spatial correlation analysis between gridded Arctic SIC and Beechey Island growth increment chronology. Right plot shows Beechey Island region enlarged. B) Plotted algal growth increment timeseries (black: anomalies = (annual value – average) / standard deviation) and NSIDC sea-ice concentrations (blue: 75 km$^2$ around Beechey Island site) (see Leclerc et al.,

2022 for original figure of subplot B). Note that growth anomalies are plotted inversely. R-value indicates strength of correlation.

Periods with larger growth increments coincide with a strongly positive AMO period and the Early Twentieth Century Warming (ETCW: 1920s-1950s) period (Fig. 4). The ETCW has been shown to be associated with sea-ice retreat in the Barents Sea caused by stronger westerly winds between Spitsbergen and Norway (Bengtsson et al., 2004), and has also been recorded by *C. compactum* Ba/Ca and growth-Mg/Ca anomaly timeseries from Spitsbergen (Hetzinger et al., 2021, 2019). Day et al. (2012) suggested the recent positive phase of AMO could explain 5-30% of satellite summer sea-ice loss and Miles et al. (2014) suggested AMO was a major driver of sea-ice variability from the past 800 years to the 1990s. Similarly, our data showed that the AMO and ETCW affected ice decline in Lancaster Sound in the mid-20$^{th}$ century. Multi-taper spectral analysis results showed multidecadal variability in the algal chronology (significant at 99% level, 60-77-year signal, CASIP: 1805–2015; Supplementary Figure S1), comparable to the posited periodicity of AMO (60–80 years) (Kerr, 2000; Schlesinger & Ramankutty, 1994). Significant (95% level) interannual signals (at 2 and 3 years) were also found, closely matching AO signatures (Supplementary Figure S1) previously shown to affect sea-ice circulation in the Baltic Sea (Jevrejeva et al., 2003). However, the CASIP multi-taper results did not capture AO's decadal variability as reported elsewhere (Ramos da Silva & Avissar, 2005). However, singular spectrum analysis (SSA) of the shortened CASIP record (1960-2000) identified significant variability at 7.6–10.3 years responsible for more than 60% of variance (Suplementary Figure S1). In the $AO_{SUMMER}$ record (1960-2000), most of the variability is interannual (2.5-5.1 years; details in Supplementary Text S1), a decadal signal (10.6-year) is explaining only 16.9% of total variance. In summary, multi-taper and SSA did not fully identify the 8 – 10-year AO signals previously identified through wavelet power spectrum analysis (Ramos da Silva & Avissar, 2005). This further suggests that the shared variability at the approximately 2–3-year periodicity level is what the sea-ice-AO and sea-ice-CASIP relationships are recording in the CAA.

The part of the algal record that extends earlier than the instrumental NAO record (i.e., prior to 1899), suggests colder and heavier ice conditions in the 19$^{th}$ century in comparison to the 20$^{th}$ century similar to the findings of indirect (temperature) sea-ice proxy tree ring records (D'Arrigo et al., 2003; Young et al., 2012). The algal chronology also suggests a period of less ice in the mid-1800s possibly due to more positive AO/NAO or AMO, or both (Fig. 4). While, many have suggested that the Little Ice Age and colder conditions persisted until the late 1800s, this slightly warmer period in the mid-1800s is supported by multiple Arctic proxy records that find episodic warming at this time (Jennings & Weiner, 1996; Massé et al., 2008: records synthecized in Miles et al., 2020). This warming period is also corroborated by ice cap stratigraphy from nearby Devon Island, Greenland ice sheets and marine cores from the Labrador Sea, which suggested early warming in 1860s and a more intense warming trend beginning around 1890 (Keigwin et al., 2003; Koerner, 1977; Trusel et al., 2018). The mid-1800s mild warming period found in our record predates those found in other AMO proxy records from terrestrial archives (e.g., Gray et al., 2004), which shows a later warming period later in the 1800s, and cooler 1830s-1840s (Fig. 4). While, some suggest some uncertainty in terrestrial AMO records (e.g., Miles et al., 2020), it is notable that sea-ice and NAO trends have been shown to lead AMO variability in some regions, and that the timing in AMO peaks and troughs are regionally variable (Alexander et al., 2014; Peterson et al., 2015). As the NAO and AO are highly correlated (Rigor et al., 2002), this could also apply to AO precursers to AMO.

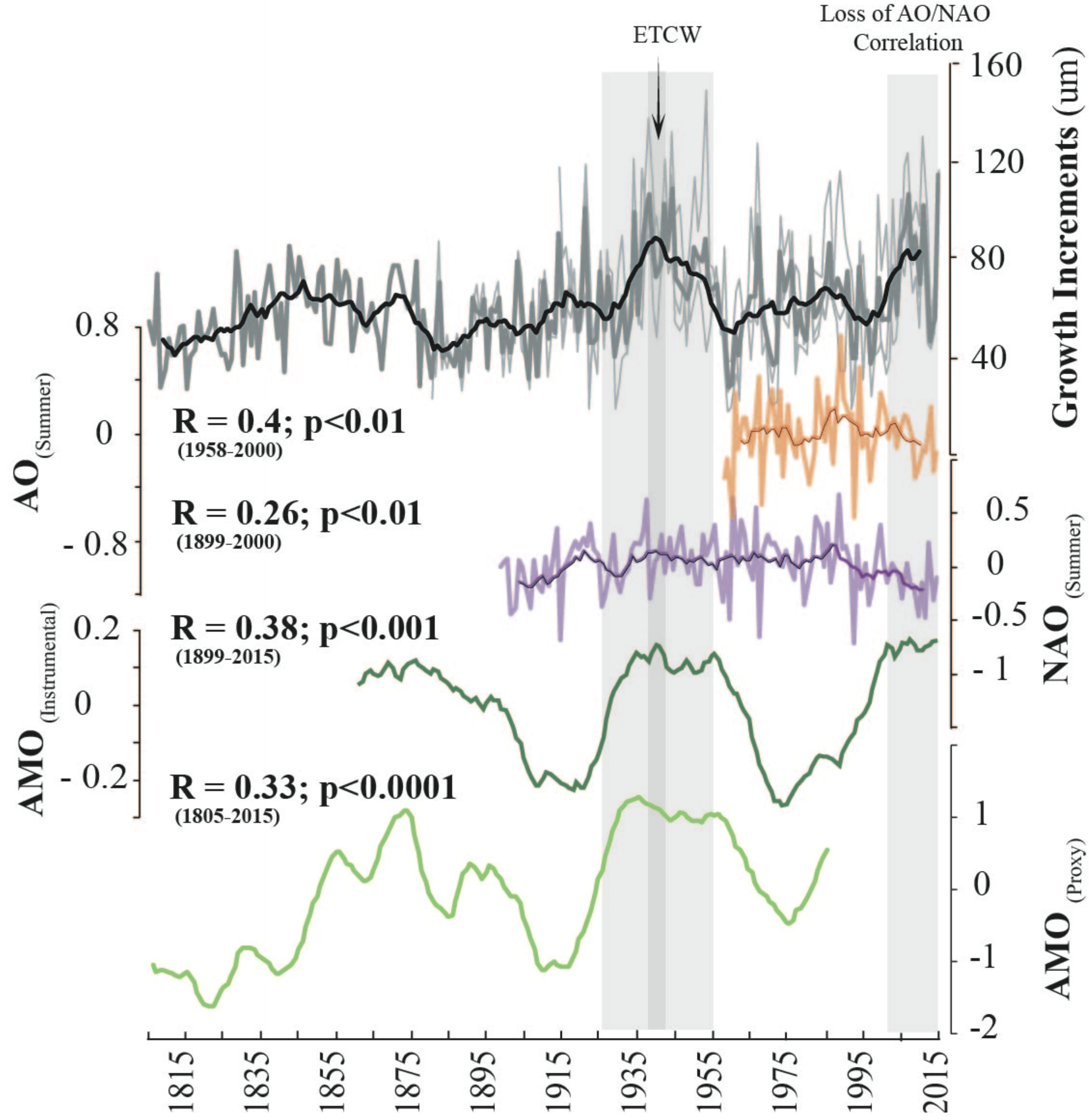


**Figure 4.** Relationship between crossdated Beechey Island growth increment (i.e., CASIP) detrended chronology and detrended AO (orange), NAO (purple) and AMO (dark green) climate indices for summer months (May-October). Individual algal samples (light grey); average of all algal samples (dark grey); 10-yr running mean of average growth, AO and NAO (black, dark orange, and dark purple lines, respectively). Tree ring-based proxy AMO timeseries (light green) from Gray et al. (2004). AMO is 10-year averaged index (no 10-yr running mean). Early

Twentieth Century Warming (ETCW: 1920-1960) and loss of correlation in 2000s periods (grey bars), and major El Niño event (arrow: 1939-1942).

Algal-sea-ice-proxy (CASIP) records are indicators of a combination of sea-ice variables affecting light penetration to the benthos: present/absent ice cover (related to melt/freeze up and wind and current dynamics), seasonal duration of cover, thickness and snow cover. Together, the AMO, AO, and NAO have the capacity of affecting all these variables. Samelson et al. (2006) suggested that the formation of land-fast ice in the CAA is controlled by both winds and air temperature, both are parameters influenced by these large atmospheric and ocean temperature patterns. Furthermore, Peterson et al. (2012) found that monthly longshore wind anomalies in the Beaufort Sea, which are heavily influenced by AO, stimulated 43% of Lancaster Sound's volume transport anomaly variance. This is supported by the significant relationship between the Beechey Island CASIP record and gridded sea-ice concentrations on the exterior CAA coast bordering the Beaufort Sea (Fig. 2a). The linked variability and coupling of the AO/NAO and AMO are posited to stem in part from interannual and long-term sea-ice cover trends and/or stimulation of Atlantic Meriodinal Overturning Circulation (AMOC) (Medhaug et al., 2012; Peterson et al., 2015; Polyakov et al., 2010; Polyakov et al., 2005; Yang et al., 2016). Our results seem to support the assertion of arctic sea-ice's important role in AMO variability.

**Table 1.** Linear regression (R- and p-values) correlations of Beechey Island algal growth record to climate indices at seasonal (summer) and decadal (10-year running means of summer values) resolutions. Highlighted grey boxes are significant positive correlations (p<0.5; darkest shades indicate p<0.01).

| **AO (May-Oct: 1958 -)** | | **NAO (May-Oct: 1958 -)** | | **AMO (Annual: 1861 -)** |
|---|---|---|---|---|
| **Seasonal** | **Decadal** | **Seasonal** | **Decadal** | **Decadal** |
| **Anomalies (- 2015)** | | | | |
| 0.23<br>p=0.08 | -0.11<br>p=0.4 | 0.05<br>p=0.7 | -0.49<br>p<0.001 | 0.31<br>p= 0.001 |
| **Anomalies (- 2000)** | | | | |
| 0.41<br>p<0.01 | 0.41<br>p<0.01 | 0.33<br>p=0.03 | 0.53<br>p<0.001 | 0.21<br>p= 0.01 |
| **Detrended (- 2015)** | | | | |
| 0.17<br>p=0.2 | -0.37<br>p<0.01 | 0.08<br>p=0.55 | -0.4<br>p<0.01 | 0.39<br>p<0.001 |
| **Detrended (- 2000)** | | | | |
| 0.4<br>p<0.01 | 0.31<br>p<0.05 | 0.34<br>p<0.05 | 0.64<br>p<0.001 | 0.38<br>p<0.001 |
| Note. All negative correlations are considered insignificant. | | | | |

## 5 Summary & Conclusion

The *C. compactum* growth increment chronology from Beechey Island recorded: 1) lower sea-ice cover during the 1800s in comparison to the 1900s; 2) slightly lighter sea-ice years in the mid-1800s; 3) the Earth Twentieth Century Warming period; 4) significant sea-ice response to AMO throughout the record; 5) significant sea-ice responses to AO/NAO from 1960-2000, and; 6) lack of sea-ice response to AO/NAO from 2000-2015 possibly due to external factors such as the greenhouse gas (GHG) effect and ice-albedo feedbacks. The development of longer high-resolution proxy records such as CASIP timeseries is critical to understanding the role of cryospheric-atmospheric feedbacks in the many intertwined components in the global climate system (Gao et al., 2015). The Canadian Arctic Archipelago, which tends to trap multi-year ice (Howell et al., 2008; Kwok, 2015), makes up a significant part of the *Last Ice Area*, predicted to be the last arctic region to experience summer ice cover (Moore et al., 2019). As this area will become increasingly crucial in the coming years, and potentially more hazardous to naval travel (Howell et al., 2022), *C. compactum* CASIP records can provide important historical and pre-industrial baselines. While it is reasonably well understood that atmospheric patterns have an effect on sea-ice extent, the interplay between coastal sea-ice cover and atmospheric patterns, especially in the CAA is still not well understood. Here we find strong links between internal variability and sea-ice trends. However, we note that these links are muted in recent decades (especially after 2000) due to anthropogenic forcing and possibly enhancement of ice penetration through QEI gates in the Canadian Arctic Archipelago (Howell et al., 2023).

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**Open Research**
This article contains original data (algal chronologies 1805-1870) and previously published data (algal chronologies 1871-2015) which is available in (Leclerc et al., 2022). Original data extend the previously published record. All coralline red algae data sets have been submitted to the NOAA National Centers for Environmental Information Paleoclimatology Data Repository (*awaiting official doi*). Primary data sets for this research are also included in figures and Supporting Information S1 files. Environmental data sets include: The monthly AO Index values were extracted from KMNI Climate Explorer (based on Trenberth & Paolino, 1980). Monthly Hurrell North Atlantic Oscillation (NAO) index values were extracted from NCAR Climate Data Guide (https://climatedataguide.ucar.edu/). Monthly AMO 10-year running mean values smoothed from the Kaplan SST V2 were extracted from NOAA PSL1 (http://www.psl.noaa.gov/data/timeseries/AMO/). Spatial correlation analysis and linear regression to monthly NSIDC sea-ice concentration dataset (Version 3: https://nsidc.org/data/g02202; Peng et al., 2013; Meier et al., 2017; see procedure in (Leclerc et al., 2021) was computed using Matlab and m_map mapping toolbox. The software kSpectra described in Ghil et al. (2002) was used to run multi-taper and singular spectral analyses.

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*Geophysical Research Letters*

Supporting Information for

# Growth increments of coralline red alga *Clathromorphum compactum* capture sea-ice variability links to Atlantic Multidecadal and Arctic Oscillations (1805 – 2015)]

**N. Leclerc[1,2], J. Halfar[1], S. Hetzinger[3], A. Tsay[4], and G. W. K. Moore[1]**

[1] Chemical and Physical Sciences Department, University of Toronto Mississauga, 3359 Mississauga Road N., Ontario, L5L 1C6, Canada

[2] Department of Archaeology, Memorial University of Newfoundland, 210 Prince Philip Dr., Newfoundland & Labrador, A1C 5S7

[3] Christian-Albrechts-Universität zu Kiel, Institut für Geowissenschaften, Ludewig-Meyn-Str. 10, 24118 Kiel, Germany.

[4] Department of Earth Sciences, University of Geneva, Rue des Maraichers 13, 1205, Geneva, Switzerland

## Contents of this file



## Introduction

The contents of this supplement relate to our study which showed a sea-ice response to Atlantic Multidecadal Oscillation (AMO) and Arctic Oscillation (AO) in Lancaster Sound located in the Canadian Arctic Archipelago. These findings were based on growth increment-based timeseries from coralline red algae, *Clathromorphum compactum*, stated in the study as the coralline-algal-sea-ice-proxy (CASIP) record. The supplement provides comprehensive spectral analysis results (extracted the kSpectra software: methods and techniques described in Ghil et al., 2002) including comprehensive explanation of both multi-taper and single spectrum analysis (**Text S1**) and visual representation of multi-taper results (**Figure S1**) showing shared signal frequencies between CASIP and AMO/AO. Periods of time investigated relate to those of relevance to either the availability of reliable instrumental datasets (i.e., AO), the length of the entire CASIP record (1805-2015), or may be cut-off at 2000 due to documented loss of correlation between AO and sea ice cover. To specify, spectral analysis on AO was only conducted on summer index values (average of May to October).

**Text S1.**

Multi-taper spectral analysis identifies oscillation signals in the algal and instrumental chronologies by maximizing signal resolutions through a number of tapers, with statistical significance being independent of signal amplitude (Ghil et al., 2002). Multi-taper results showed a highly significant (99% level) 60-77-year signal in the algal chronology (ASIP: 1805–2015) (Figure S1d), comparable to the posited periodicity of AMO (60–80 years) (Kerr, 2000; Schlesinger & Ramankutty, 1994). Significant (95% level) signals at 2.3 and 3 years were also found (Figure SId), closely matching AO (Figure S1a) signatures also previously shown to affect sea ice circulation in the Baltic Sea (Jevrejeva et al., 2003).

A previous study on instrumental AO periodicity found an 8–10-year signal present since 1960s through wavelet power spectrum analysis (Ramos da Silva & Avissar, 2005). Multi-taper spectral analysis of the algal timeseries since 1960, however, only showed a significant multi-taper signal of 2–2.7-year in the ASIP record (1960-2015 and 1960-2000) and a 2.9-year signal in the $AO_{SUMMER}$ record (1960-2015) (Figures S1a, S1b and S1c). This shared signal of approximately 2–3 years in algal and $AO_{SUMMER}$ timeseries supports their AO and ASIP co-variability, however, surprisingly did not show the 8–10 year signal of the AO as previously reported (Ramos da Silva & Avissar, 2005).

Unlike multi-taper spectral analysis that reduces the variance of spectral estimates, singular spectrum analysis calculates total variance and estimates the amount of co-variability of signals through lagging techniques, and was specifically designed for short and noisy timeseries (Ghil et al., 2002). Accordingly, singular spectrum analysis of the shortened ASIP record (1960-2000) identified at the 95% confidence level a 10.3-year signal responsible for 34.9% variance, a 7.6-year signal for 27.8%, a 3.4-year signal for 19.1%, and 2.6-year for 18.3%. This suggests that 7.6 – 10.3-year signals were responsible for more than 60% of ASIP variance. In the $AO_{SUMMER}$ record (1960-2000), most of the variability is captured in signals of 5.1-years, 3.4-years and 2.5-years (responsible for 22.8%, 28.2% and 32.1% variance, respectively), with a 10.6-year signal responsible for only 16.9% of total variance. In addition, results of singular spectrum analysis for the 1805–2015 period pointed to a 33-55-year signal in the algal record responsible for 29.3 % of variance, a 3–6-year signal for 13.1 % of variance and 10–17-year signal for 17.2 % of variance, quite similar to sea ice-AO responses in the Baltic Sea (2.2–3.5, 5.7–7.8, and 12–20-year signals: Jevrejeva et al., 2003) (Figure S1d). Multi-taper and singular spectral analyses did not fully identify the 8 – 10-year AO signals previously identified through wavelet power spectrum analysis (Ramos da Silva & Avissar, 2005). This further suggests that the shared variability at the approximately 2–3-year periodicity level is what sea ice-AO and sea ice-ASIP are recording.

**Figure S1.** Multi-taper spectral analysis for the Beechey Island algal growth increment timeseries (CASIP) and $AO_{SUMMER}$ for time periods discussed in text. Red lines indicate 99% and 95% level of significance.