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## The 18.6-year lunar nodal cycle may affect ecosystems on the Northwest Atlantic continental shelves

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### Abstract :

As one of the foremost global forcings, tidal circulation exerts a pervasive influence on biological and physical processes occurring in the world's oceans on hourly to decadal time scales. This research identified the 18.6-year periodic variation in the lunar orbital plane within an annually resolved 140-year (1875 to 2015) shell growth master chronology measured from 21 live collected *Arctica islandica*, a bivalve known to be one of the longest lived non-colonial animals. The potential ecological implications of this result warranted detailed inventory of underlying physical processes. The absence of long-term in situ hydrological data for the bivalve's habitat was circumvented by the use of satellite data and numerical modeling which show that coastal regions of the Northwest Atlantic shelf clearly record diurnal tidal currents influenced by the 18.6-year nodal lunar cycle. The approach described here demonstrates that combining physical and biological data can help to identify subtle ecological processes over long time-scales for accurately disentangling the latter from variation introduced by anthropogenic climate change.

### Highlights

► The astronomical 18.6-year nodal tidal cycle (18NTC) influences a bivalve (*A. islandica*) growth variability in Saint-Pierre and Miquelon archipelago (SPM). ► Sea Surface Temperature bidecadal variability in SPM region is partly related to 18NTC. ► 18NTC influences vertical mixing of some regions of the NW Atlantic shelf.

**Keywords** : *Arctica islandica*, Tides, Northwestern Atlantic continental shelf, Sclerochronology, Growth

# 31 1. Introduction

32 Marine ecosystems experience environmental forcings over temporal scales ranging from a  
33 few hours to several decades. A detailed understanding of these environmental variations and their  
34 influence on living organisms on multidecadal time scales is critical for understanding and predicting  
35 how ecosystems will respond to anthropogenic climate change.

36 The marine environment includes parameters that determine benthic invertebrate lifestyles and  
37 growth trajectories. Parameters such as temperature, nutrient availability and associated primary  
38 production mainly depend on complex ocean-atmosphere interactions, but also on tides, a highly  
39 predictable astronomical forcing that particularly influences coastal regions on a synchronized global  
40 scale. As deterministic processes, tides appear primarily as semi-diurnal and diurnal variations in sea  
41 level, but also exhibit several long-term oscillations including the 18.61-year nodal tidal cycle

42 (hereafter 18NTC). This cycle arises from the fluctuation of the lunar orbital plane, which on average  
43 has a 23.4° angle relative to Earth's equatorial surface, but also varies consistently between 18.3° and  
44 28.6° over a period of 18.61 years. This results in semi-diurnal and diurnal modulation of sea levels and  
45 currents that vary according to the lunar and solar components of the tide. The major diurnal tidal  
46 components, O1 and K1, have respective periods of 25.82 and 23.93 hours that vary between +/- 19%  
47 and 14% (respectively) over a period of 18.61 years. The main semi-diurnal tidal component M2 varies  
48 by +/- 4% in phase opposition with the diurnal tidal components (Godin, 1972). For a rigorous  
49 description of the nodal cycle see Ray (2007), specifically the comprehensive appendix herein. The  
50 18NTC modulation of sea levels can reach a maximum of 30 cm across continental shelf environments,  
51 a range that will contribute to coastal flooding with the ongoing sea-level rise (Peng et al., 2019).  
52 However, outside the coastal strip, sea-level variation of a few tens of centimeters with bidecadal  
53 periodicity has not been much studied or detected in pelagic or benthic marine environments (Ray,  
54 2007).

55 Nevertheless, the 18NTC modulation of tidal currents has the potential to influence vertical  
56 mixing of the water column by the same well-documented physical processes that govern the ~14-day  
57 spring-neap tidal cycles, but over a nearly bidecadal period. This implies that the diurnal tidal currents  
58 were stronger worldwide during 1969, 1988, 2006-2007 and weaker in 1978-1979, 1997 and 2016 for  
59 the last decades. The reverse is true for the semi-diurnal tidal currents but to a lesser extent. Tidal  
60 currents contribute to seawater mixing either through friction on the seabed or by the generation of  
61 internal waves that produce strong vertical shear and enhance vertical mixing. Thus, an increase in  
62 vertical mixing may lead to greater downward transport of solar heat and greater upward transport of  
63 nutrients to the euphotic layer in summer. This transport can lower the sea surface temperature (SST),  
64 but increase temperature along the sea bottom (i.e., in the benthic environment). The influence of the  
65 18NTC may thus appear in regions experiencing pronounced diurnal tidal currents due to the stronger  
66 fluctuations. This 18NTC effect was first reported by Loder and Garrett (1978) using coastal seawater  
67 temperatures records in British Columbia (southwestern Canada). More generally, the North Pacific is  
68 a region where water properties can be influenced by the 18NTC. 18NTC signals have in fact been  
69 observed in current and temperature data from the Northeast Pacific region (McKinnell and Crawford,  
70 2007), the Bering Sea (Osafune and Yasuda, 2010) and the Northwest Pacific (Osafune and Yasuda,  
71 2006). Only a very few studies have documented 18NTC effects in the Atlantic Ocean. Recently,  
72 (Agosta, 2014) showed that 18NTC effects appear in SST variability around the Malvinas Islands  
73 (Southwest Atlantic) in association with ocean-atmosphere interactions whose variability may affect  
74 summer precipitation in the southwestern Andes.

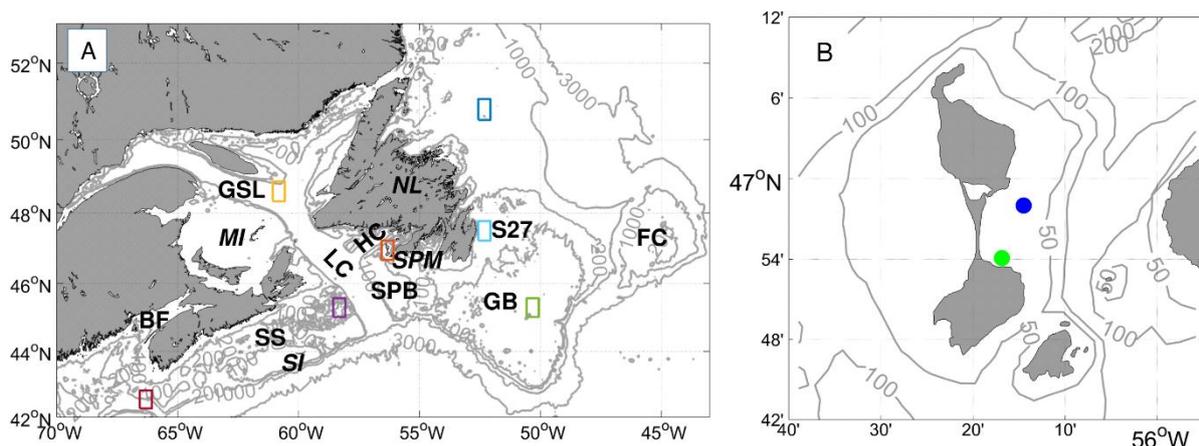
75 To our knowledge, the 18NTC has never been detected from individual living organisms,  
76 because such detection would require accurate long-term environmental datasets against which to  
77 evaluate the growth record. Long-lived, sessile species that continuously build exoskeletons  
78 throughout their lives are ideal candidates for detecting the 18NTC signal. The bivalve *Arctica islandica*  
79 is the longest lived, non-colonial animal forming periodic growth patterns (Butler et al., 2013). Like  
80 other mollusks, this species constructs a shell with distinct annual growth increments defined by  
81 annual growth lines formed during periods of reduced growth shell (Schöne, 2013). With this periodic  
82 banding, each increment can be articulated into an annual, long-term record. Moreover, if the date of  
83 a specific growth increment is known (for example the date of death), it is then possible to assign  
84 precise calendar dates to an entire shell record. Based on synchronous changes in shell growth rates,  
85 time series of increment widths for specimens having overlapping lifespans and collected from the  
86 same locality can be combined to build composite or master chronologies (Schöne, 2013; for a review).  
87 Annual increment widths generally record the organism's physiological interactions with its  
88 environment (Butler et al., 2013). Although genetic factors can influence ontogenetic growth trends  
89 and other fitness-related traits (David et al., 1995), year-to-year variability in shell growth arises mainly  
90 from environmental factors (Marchitto et al., 2000).

91

92 The site of bivalve sampling is the Saint-Pierre and Miquelon (SPM) archipelago, two small  
 93 French islands located in Canadian waters located in southwestern Newfoundland (Fig. 1A). Sea level  
 94 tidal variability is considered semi-diurnal in the region as the M2 and S2 components (0.60 and 0.17  
 95 m respectively) dominate the diurnal O1 and K1 components (0.07 and 0.06 m respectively) in Saint-  
 96 Pierre harbor. Recent studies have shown new characteristics of SPM coastal waters little studied in  
 97 the past (Lazure et al., 2018; Poitevin et al., 2019). Lazure et al. (2018) showed the extreme variability  
 98 of the bottom temperatures ( $> 11.5$  °C at depths of 30–60 m) at a diurnal tidal frequency during the  
 99 stratified period (i.e., late spring to early fall). Furthermore, previous sampling in shallow coastal  
 100 waters of the SPM (15 m depth) has shown the sensitivity of *A. islandica* to high-frequency dynamics  
 101 (Poitevin et al., 2020), but also to regional circulation at the scale of the NW Atlantic (Poitevin et al.,  
 102 2019).

103 Following further sampling of *A. islandica* in stratified waters, the first objective of this study  
 104 was to assess a potential 18NTC footprint in *A. islandica* shells at this site theoretically conducive to  
 105 producing visible traces of 18NTC through modulations in tidal mixing and thus in growth increments  
 106 of *A. islandica* shells. The converging evidence for this influence then led us to expand our exploration  
 107 to a regional scale and hypothesize that 18NTC may act on a larger scale on the NW Atlantic shelf.  
 108

109 This paper is organized as follows. In Section 2, we describe *A. islandica* growth patterns over  
 110 141 years. Section 3 is dedicated to a spectral analysis of the master chronology and reconstruction of  
 111 a time series with an 18.6-year period to compare with the astronomical 18NTC. Strong correlations  
 112 between these two series led us to assess the environmental conditions underlying these long-term  
 113 modulations. In Section 4, we describe the tidal dynamics around SPM and present its role on  
 114 temperature variability near SPM. Satellite SST is then used to explore the SST bidecadal variability in  
 115 SPM and look for a relationship with the 18NTC. We then extend the local SPM SST-18NTC relationship  
 116 analysis to regional-scale coastal areas around the NW Atlantic. In Section 5, we use a numerical model  
 117 to verify that areas experiencing bidecadal SST variability in phase opposition with the 18NTC broadly  
 118 correspond to continental shelf areas where diurnal currents predominate, strongly suggesting that  
 119 the 18NTC influences vertical mixing in those areas. Our results indicate that the 18NTC may influence  
 120 marine ecosystems on regional scales. In Section 6, we discuss the limitations of this study and note  
 121 further analyses that can help resolve areas of uncertainty.



122  
 123 **Fig. 1.** (A) Location of Saint-Pierre and Miquelon (SPM) Archipelago (orange rectangle), NL:  
 124 Newfoundland Island, MI: Magdalen Islands, SI: Sable Island, GSL: Gulf of Saint Lawrence, FC: Flemish  
 125 Cap, LC: Laurentian Channel, SS: Scotian Shelf, HC: Hermitage Channel, SPB: Saint-Pierre Bank, GB:  
 126 Grand Banks, BF: Bay of Fundy. Isobaths (3000, 1000, 200, 100 m) are displayed. Colored rectangles  
 127 indicate locations of SST time series analyzed in section 4. (B) SPM Archipelago. Blue dot: sampling  
 128 site (24–25 m depth) for *Arctica islandica* (this study). Green dot: sampling site (14–15 m depth) for  
 129 *A. islandica* (Poitevin et al., 2019).

## 130 2. Construction of *Arctica islandica* master chronology

### 131 2.1. *Arctica islandica* sclerochronological preparation

132 A total of 21 *A. islandica* shells were cut, polished and etched in Mutvei's solution using the  
133 sclerochronological procedures described in (Poitevin et al., 2019). Shell sections were then  
134 photographed under reflected light (Carl Zeiss, KL 2500 LCD) using an AxioCam MRC 5 installed on a  
135 Carl Zeiss SteREO Lumar.V12 stereomicroscope equipped with a motorized stage and adjusted to 25×  
136 magnification. Photomosaics were constructed using AxioVision 4.9.1 software (Carl Zeiss) and  
137 resulting images were processed with Image J software (NIH Image) to identify and measure the  
138 growth increment widths. Increments were measured perpendicular to increment boundaries at a  
139 consistent distance, halfway between the outer and inner boundaries of the outer shell layer on the  
140 margin (Mette et al., 2016; Poitevin et al., 2019; Schöne, 2013). To obtain a robust annually-resolved  
141 chronology, the growth increment series of live-collected specimens were cross-dated since the year  
142 of death (2016) of these specimens was known. Cross-dating describes the process of matching  
143 temporally overlapping time series based on synchronous growth increment patterns induced by  
144 common external drivers. Individual growth increment measurements were initially compiled and  
145 statistically analyzed using the dplR program (Bunn, 2008) to aid in intershell year-to-year growth  
146 comparisons. The statistical crossdating program COFECHA (Grissino-Mayer, 2001) was also used to  
147 further verify the first crossdating results. Errors in the chronology identified by dplR and COFECHA  
148 were manually reinvestigated and corrected. This yielded a time series of increment width for each  
149 individual (available online: <https://doi.org/10.5281/zenodo.6823144>).

150 To develop a master chronology, time series of individual increment widths were detrended using  
151 negative exponential functions. This deterministic detrending method was chosen as it largely  
152 preserves environmental signals that fluctuate over long time periods (Marali and Schöne, 2015;  
153 Peharda et al., 2021; Schöne, 2013).

154 Growth indices (GIs) were then calculated for each year and each individual by dividing the measured  
155 increment width by the predicted increment width (Schöne, 2013) as follows:

$$156 \quad GI_t = \frac{L_{t+1} - L_t}{L(p)_{t+1} - L(p)_t}$$

157 Where  $GI_t$  is the growth index at time  $t$  (in years),  $L_{t+1} - L_t$  is the measured shell increment at  $t$  and  $L(p)_{t+1}$   
158  $- L(p)_t$  is the predicted shell increment length at the same time  $t$ .

159 Individual time series of the GI were then standardized as follows (Schöne, 2013):

$$160 \quad SGI_t = \frac{GI_t - \mu}{\sigma}$$

161 where  $\mu$  is the average of all GI values and  $\sigma$  the standard deviation. The standardized GI (SGI) is a  
162 dimensionless measure of how growth deviates from the predicted trend. Positive values represent  
163 greater than expected growth, whereas negative values represent less than expected growth.

164 The quality of the chronology was quantified using the expressed population signal (EPS) statistic  
165 (Wigley et al., 1984):

$$166 \quad EPS = \frac{n * R_{bar}}{(n * R_{bar} + (1 - R_{bar}))}$$

167 where  $R_{bar}$  is the average of all correlations between pairs of SGI chronologies and  $n$  is the number of  
168 specimens used to construct the stacked chronology.

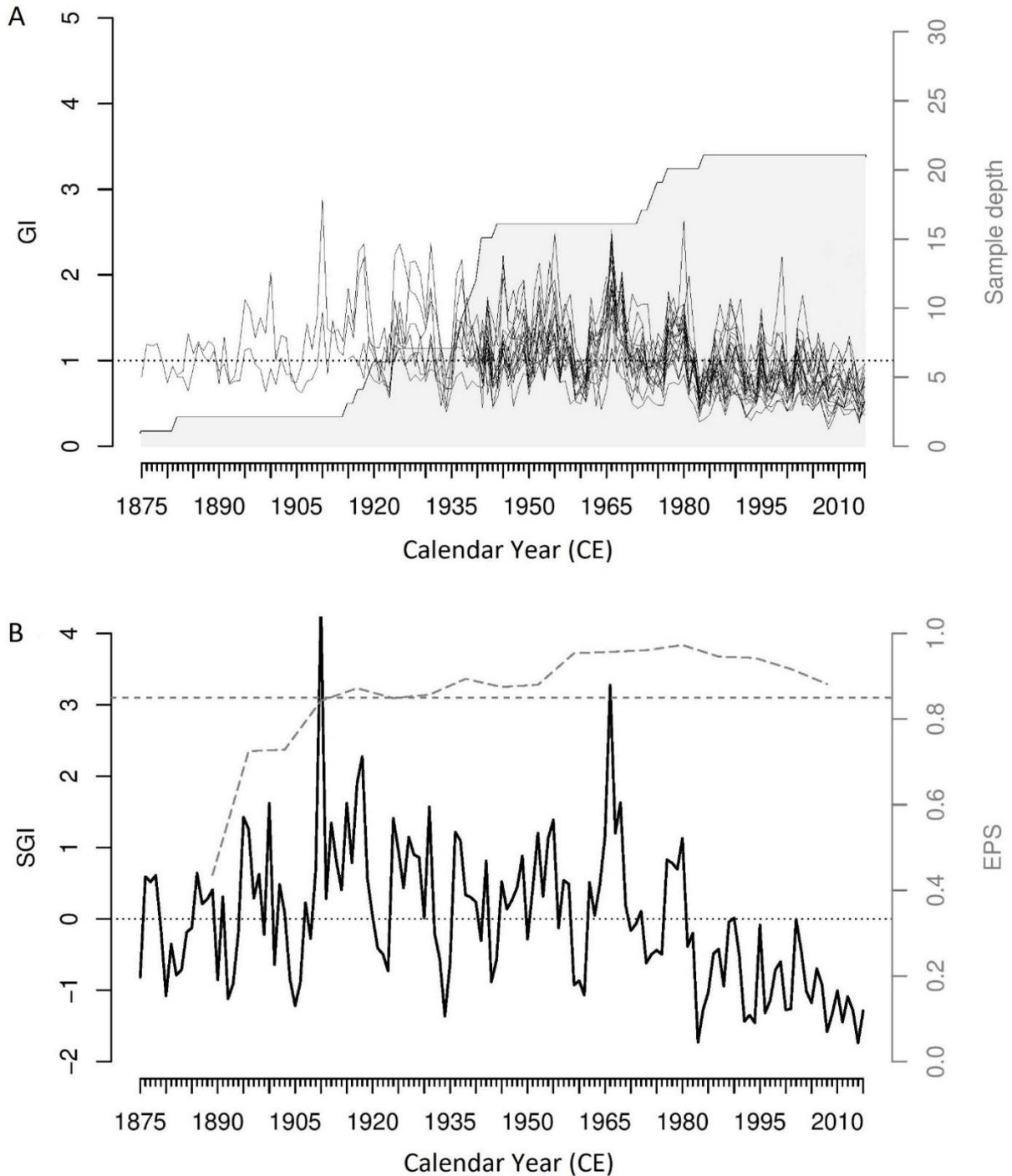
169 Although there is no analytical threshold for this statistic, EPS values higher than 0.85 are interpreted  
170 to indicate that the variance of a single SGI chronology sufficiently expresses the common variance of  
171 all SGI series. All these analyses were carried out using the R package dplR (Bunn, 2008).

## 172 **2.2. Growth chronology construction**

173 Twenty-one live *A. islandica* specimens were collected by scuba divers in September 2016 in  
174 circalittoral zone (water depths of 24–25 m) along the southeastern shore of the sandy Miquelon-  
175 Langlade isthmus (Fig. 1B). The sampling area consisted of homogenous, compacted, stable and well-  
176 graded fine-grained sand (85% of its mass between 100 and 200  $\mu\text{m}$ ).

177 The shell-based growth record covers the time period from 1875 to 2015. The shortest and longest  
178 individual time series records used to build the master chronology were 32 and 141 years, respectively.  
179 The average length of the 21-time series was 78.24 years ( $1\sigma = 20.27$ ). Based on the individual growth  
180 indices (GI), shells present a strong and synchronous growth pattern among individuals (Fig. 2A).  
181 Individual growth records were combined to calculate SGI values (Fig. 2B). These dimensionless  
182 measures document how average annual growth deviates from the predicted trend. Positive SGI values  
183 represent greater than expected growth, whereas negative SGI values represent less than expected  
184 growth. Since the 1980s, even when SGI time series follow a zigzag pattern alternating between high  
185 and low values, the SGI values have remained mainly negative, similar to shallower *A. islandica*  
186 specimens from SPM (14–15 m depth; (Poitevin et al., 2019)). The running EPS calculated over a 15-  
187 year window with 8-year overlap indicates that the variance in individual growth chronology  
188 sufficiently expresses the common variance of all GI series after 1905. Synchronous shell growth was  
189 also noted prior to this period. The overall series exhibited an intercorrelation of 0.526 and an average  
190 mean sensitivity calculated according to Eq. 2 in (Biondi and Qeadan, 2008) of 0.239.

191 For the sake of comparison, we also interpreted a shell growth master chronology described in  
192 (Poitevin et al., 2019) from a nearby *A. Islandica* locality (green circle in Fig. 1B) sampled in infralittoral  
193 zone (water depths of 14-15 m) and where the water column is nearly vertically homogeneous. This  
194 chronology extends over 166 years (1850-2015) and will be referred to hereafter as the infralittoral  
195 SGI.



196

197 **Fig. 2.** *Arctica islandica* master chronology. (A) Individual detrended growth index (GI) time series and  
 198 number of shells used in the chronology (sample depth). The horizontal gray dotted line crossing 1 on  
 199 the GI axis distinguishes measured annual increments widths larger ( $GI > 1$ ) and smaller ( $GI < 1$ ) than  
 200 predicted (negative exponential functions). (B) Standard growth index (SGI) master chronology (black  
 201 curve) and expressed population signal (EPS) values (gray dashed curve). The horizontal gray dotted  
 202 line crossing 0 on the SGI axis distinguishes positive and negative SGI values. The horizontal gray  
 203 dashed line represents the EPS threshold of 0.85 above which the master chronology is typically  
 204 considered to be statistically robust (Wigley et al., 1984).

## 205 3. Analysis of *Arctica Islandica* master chronology

### 206 3.1. Spectral analysis

#### 207 3.1.1. Methods

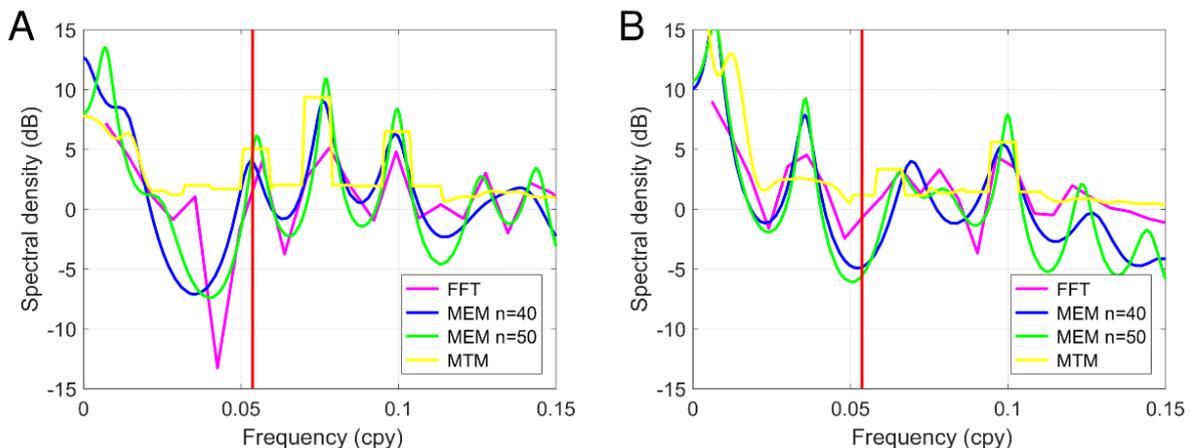
208 Three spectral methods were used to detect frequencies: a Fourier transform, the maximum  
209 entropy method (MEM, sometimes called maximum entropy spectral analysis (MESA) (Padmanabhan  
210 and Rao, 1988)) and the multi-taper method (MTM) (Thomson, 1982). The fast Fourier transform (FFT)  
211 simply considered the entire SGI time series (N=141) for the spectrum shown in Fig. 3A.

212 The second method (MEM) is an autoregressive model proposed by (Burg, 1967) that allows a  
213 better resolution than Fourier transform, but is parametric in the sense that the order of the model  
214 must be specified. As model order increases, spurious peaks may appear and results must be  
215 interpreted with caution. A wide range of methods can be used to determine model order. This study  
216 estimated orders using the panel of frequencies we targeted and assuming a bidecadal period to test  
217 for robustness.

218 The MTM technique (Ghil et al., 2002) uses a set of orthogonal tapers that are designed to  
219 reduce spectral leakage. This method can also detect harmonic frequencies and oscillations with  
220 constant phase over the entire series. We used the freely available SSA-MTM Toolkit for spectral  
221 analysis (<http://research.atmos.ucla.edu/tcd/ssa/>).

#### 222 3.1.2 Spectral analysis of the standardized growth index (SGI) and the infralittoral SGI

223 Figure 3A shows results of the FFT, MEM with different model orders (40 and 50) and the MTM spectral  
224 methods for the low frequency ( $< 1/6.6$  year) component of the spectra. The three different methods  
225 gave similar results, with three spectral peaks indicating periods of  $\sim 18$  years,  $\sim 13$  years and  $\sim 10$  years  
226 for frequencies lower than 0.15 cycles per year (cpy). The infralittoral SGI master chronology (Fig. 3B)  
227 shared a common 10-year spectral peak and a 28-year spectral peak detected only by MEM.  
228 Interestingly, the  $\sim 18$  year frequency is not detected in this latter time series. These results led us to  
229 continue with the recomposition of the SGI series at periods close to 18 years to compare it with the  
230 astronomical nodal cycle.



231

232 **Fig. 3.** (A) Power spectra from the standardized growth index (SGI) time series, (B) Power spectra from  
233 the infralittoral SGI time series (Poitevin et al., 2019). Fast Fourier Transform (FFT): magenta; Maximum  
234 Entropy Method (MEM) with filter length=40: blue, length=50: green; Multi-Taper Method (MTM):  
235 yellow. Vertical red line shows the frequency of the nodal tidal cycle (0.0537 cycles per year (cpy)  
236 corresponding to a period of 18.6 years).

## 237 **3.2. Reconstruction of the *Arctica islandica* growth index with an 18.6-year period**

### 238 3.2.1 Methods

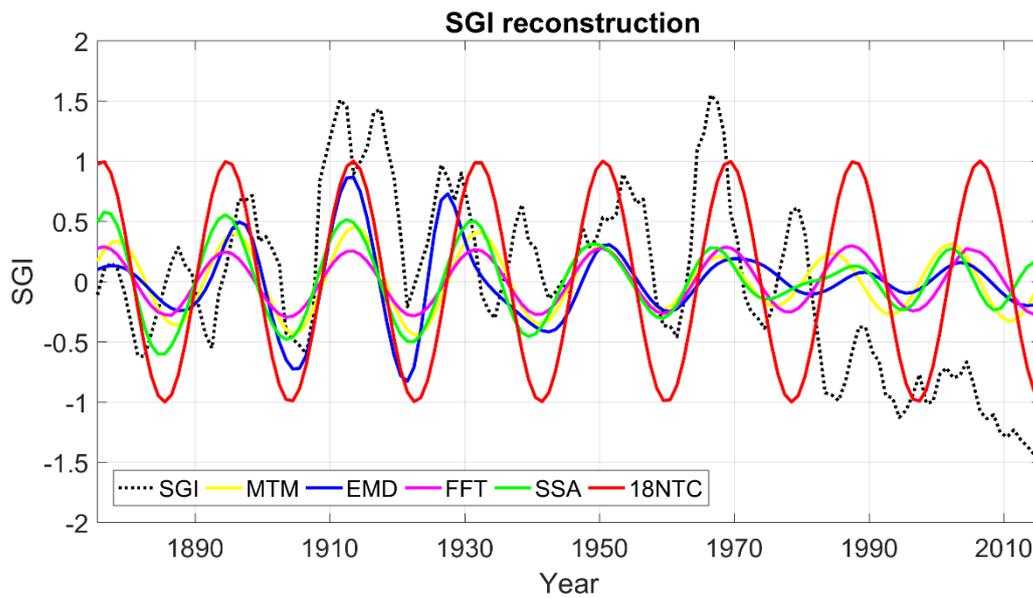
239 The FFT reconstructions were based on the same series, but truncated of the 11 most recent  
240 or oldest years to obtain an integer value for the number of 18.6-year cycles ( $130/18.6 \approx 7$ ). This  
241 truncation allowed to evaluate the spectral density at the frequency of  $(18.6 \text{ yr})^{-1}$  and to reconstruct  
242 the signal at this specific frequency. The two truncated time series gave similar reconstructions for this  
243 period. These were averaged over the shared period and then the entire record was assembled by  
244 completing the 11-year beginning and end intervals with each reconstruction. MTM series were  
245 reconstructed at the frequency of the detected harmonic line. Two additional methods were used to  
246 decompose the SGI time series in sequence of varying frequencies: the empirical mode decomposition  
247 (EMD) and the singular spectrum analysis (SSA).

248 The *A. islandica* SGI and SST time series (see below) were analyzed using EMD (Flandrin et al.,  
249 2004; Huang et al., 1998). EMD is a non-parametric and adaptive method that converts time series into  
250 a limited number of intrinsic mode functions (IMF) with decreasing frequencies. It does not assume  
251 any decomposition basis as trigonometric functions do for the Fourier transformation or as mother  
252 wavelets do for wavelet transformation. This method is used in many fields outside of the geosciences,  
253 including biomedicine and economics. It uses an iterative approach for which the last series, referred  
254 to as the residue, represents the trend of the original series. The main drawback of EMD is the mixing  
255 mode, which may cause different IMFs to diverge from an orthogonal orientation, thereby causing  
256 overlap of spectral content between neighboring IMFs.

257 SSA is a non-parametric method (Vautard and Ghil, 1989) that decomposes an original series  
258 into a small number of statistically independent components. It uses singular value decomposition of  
259 the correlation matrix estimated after embedding the signal into its delayed coordinates. SSA  
260 calculates a covariance matrix using the Toeplitz approach and then determines eigenvalues and  
261 eigenvectors. The principal components (PCs) are given as scalar products of the eigenvectors and  
262 time-delayed embedding belonging to the original series. Reconstructed components (RCs) are  
263 calculated by inverting the PCs and calculating the averaged anti-diagonals. The method completely  
264 reconstructs original time series by summing all of the reconstructed components. Pairs of equal or  
265 nearly equal SSA eigenvalues in approximate phase quadrature (Ghil et al., 2002) define oscillatory  
266 modes. We used an adapted version of MATLAB 2016 with the signal processing toolbox program  
267 ([https://fr.mathworks.com/matlabcentral/fileexchange/58967-singular-spectrum-analysis-beginners-  
268 guide](https://fr.mathworks.com/matlabcentral/fileexchange/58967-singular-spectrum-analysis-beginners-guide)) to perform the analysis. The embedding dimension was set to 50 and the reconstruction was  
269 done with RCs 5 and 6.

### 270 3.2.2 Reconstruction with an 18.6-year period

271 We extracted the 18.6-year period from the FFT and MTM SGI time series to compare it with  
272 a known, idealized 18NTC time series (Fig. 4). We used the formula provided in the appendix (Ray,  
273 2007) to calculate the 18NTC signal with an arbitrarily defined amplitude (+1 to -1). The EMD methods  
274 generated six IMFs. The third IMF highlights several nearly bidecadal cycles with eight maxima over  
275 141 years. SSA generated several RCs from which the sum of a pair of RC 5 and RC 6 revealed an  
276 oscillation approaching a period of 18 years.



278

279 **Fig. 4.** Master chronology time series reconstructions at an 18.6-year period over time. Yellow line:  
 280 Multi-taper method (MTM) reconstruction from harmonic components significant at the 95%  
 281 confidence interval. Blue line: third intrinsic mode function (IMF) from an empirical decomposition  
 282 method (EMD) analysis. Magenta line: inverse fast Fourier transform (FFT) reconstruction of the 18.6-  
 283 year period. Green line: singular spectrum analysis (SSA) ( $M = 45$ ) reconstruction from the sum of  
 284 reconstructed components (RCs) 5 and 6. Red line: astronomical 18.6-year nodal tidal cycle (18NTC)  
 285 (arbitrary amplitude). Black dotted line: standardized growth index (SGI) 5-year running average.

286 All methods (Fig. 4) gave roughly similar results and show that the phases remained constant  
 287 and consistent with the 18NTC phase until at least the ~1980s/90s. The shell growth anomalies are all  
 288 in phase with the 18NTC for the eight periods covered by the 1875-2015 timeframe of the SGI. Before  
 289 the 1990s, phase shifts between reconstructions and 18NTC generally did not exceed two years.  
 290 Correlation estimates between the reconstructed periodicities and the 18NTC signal varied from 0.66  
 291 for EMD to 0.99 for FFT ( $p < 0.001$ ;  $N = 141$ ) and variance ratios between the reconstructed signals and  
 292 the SGI ( $= 1$ ) ranged from 3.8 to 9.7%. These variance ratios increased to 7.3-18.3% when compared  
 293 with the 5-year smoothed SGI series.

## 294 4. Physical background and temperature observations and analysis

### 295 4.1. Tidal dynamics and hydrology in the Saint-Pierre and Miquelon archipelago

296 A recent study (Lazure et al., 2018) based on observations of coastal water temperature at 30 and 60  
 297 m depth around SPM detected strong diurnal tidal currents and diurnal bottom water temperature  
 298 oscillations exceeding  $10^{\circ}\text{C}$  during times of maximum summer stratification. These observations were  
 299 interpreted as an expression of a coastal trapped wave resonant with the diurnal frequency of the tide  
 300 rotating clockwise around the archipelago within two periods. On the eastern side of the archipelago,  
 301 the main semi-diurnal component M2 was of the same order of magnitude as the diurnal components,  
 302 but it was much weaker on the western side. In this study, only the temporal evolution of the bottom  
 303 temperatures was measured and we lacked observations in the water column except the currents  
 304 measured by Acoustic Doppler Current Profiler (ADCP). This absence of measurement was  
 305 supplemented with a SPM2017 oceanographic cruise, which consisted in measuring the temperature  
 306 profiles around the archipelago for one month.

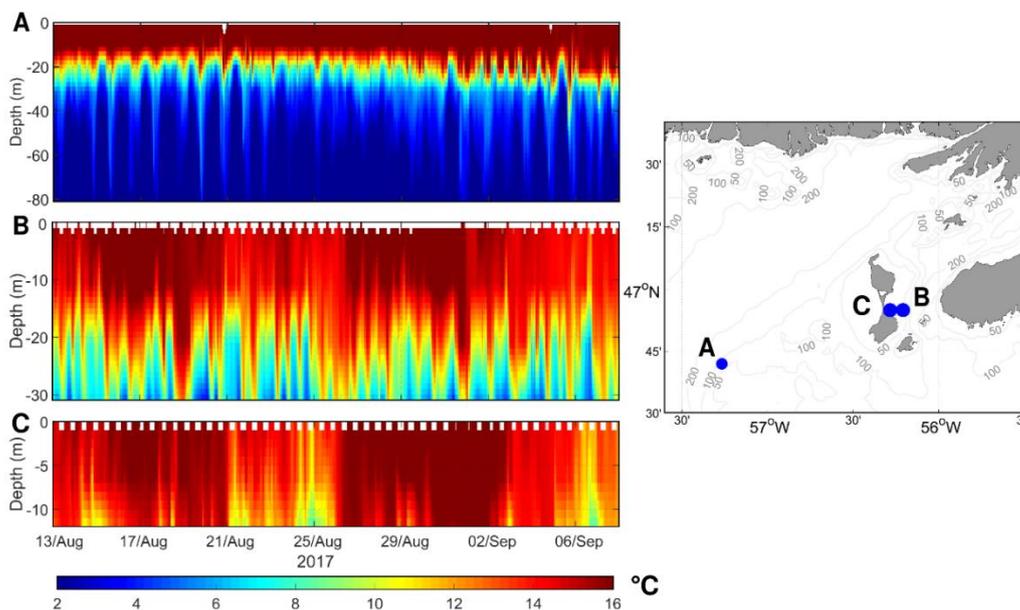
307 **4.2. Hydrology**

308 4.2.1. Seawater temperature measurements around Saint-Pierre and Miquelon

309 Moored thermistor chains with various numbers of probes were deployed during the SPM2017  
310 cruise from 13/08/2017 to 10/09/2017. At each mooring, two temperatures probes were set at the  
311 surface and the bottom and the rest of the probes were evenly distributed along the line (total of 3, 5  
312 and 9 probes at 15, 30, 80 m depth, respectively). Each probe measured temperature and pressure  
313 and was packed in a small plastic bag filled with Marcol 82 insulating oil. The acquisition time step was  
314 2 minutes. Vertical temperature profiles result from linear interpolation every 2 m from the bottom  
315 between two probes by taking into account the vertical location of each probe measured by the  
316 pressure sensor.

317 4.2.2. Variation in temperature vertical profiles over time

318 The SPM 2017 cruise extended the dataset of observations at three locations (Fig. 5).  
319 Stratification varied from nearly homogenous in shallow waters (Fig. 5C) to a maximum of 16.5°C  
320 difference between surface and bottom temperatures (Fig. 5A). In shallow waters, vertical mixing was  
321 almost permanent (Fig. 5C). Note that this site is very close to the infralittoral SGI sampling site, but  
322 the years of observation differ. Temperatures were measured near the *A. islandica* sampling site (Fig.  
323 3B) in Summer 2017 and show strong stratification and enhanced temperature variability near the  
324 bottom, confirming previous observations (Lazure et al., 2018). A diurnal signal clearly appeared with  
325 the superposition of a 2-day period, probably related to the wind effect as described in (Bezaud et al.,  
326 2020). The last station (Fig. 3A) is located on the north side of St. Pierre Bank and is the first known  
327 measurement of the temporal evolution of the temperature profile at the confluence of the Laurentian  
328 and Hermitage channels. The measurements show a clear diurnal signal, which consists of an internal  
329 wave of ~20-60 m range once a day. A tidal harmonic analysis (not shown) indicates that the main  
330 period corresponds to the O1 (25.8 h period) tidal component.



331 **Fig. 5.** *In situ* measurements of seawater temperature in °C (color scale displayed in the figure's  
332 bottom) over time and depth at 3 mooring sites near the Saint-Pierre and Miquelon archipelago  
333 (graphs A, B, C) from 2017/08/13 to 2017/09/08. The corresponding mooring locations (A, B, C)  
334 are represented by blue dots on the right panel. Blue dot (A) is located at the northern edge of the Saint-  
335 Pierre Bank (80 m depth) while (B) and (C) are situated to the east of Miquelon Island (30 m and 15 m  
336 depth).  
337

338            These measurements confirm the dominant nature of the diurnal tides in SPM area extended  
339 to Saint-Pierre Bank. However, on longer time scales, we lack observations taken on a regular basis  
340 during the 20th century to evaluate the potential presence of a nearly bidecadal cycle in environmental  
341 parameters. The only available multidecadal observations for SPM waters were SST satellite data  
342 extending back to September 1981.

### 343    **4.3 Analysis of SST in Saint-Pierre and Miquelon and the Northwest Atlantic**

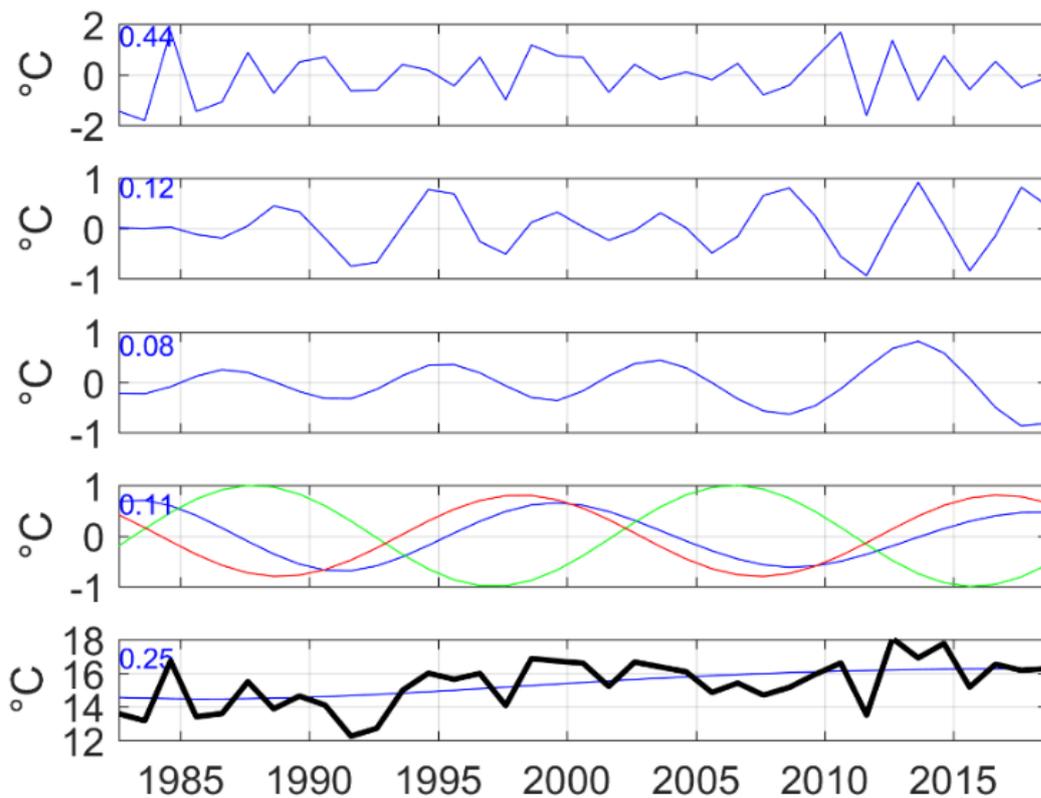
#### 344            4.3.1. SST data set

345            Long-term temperature analysis used the Pathfinder V5.3 dataset (Saha et al., 2018) with a  
346 squared grid cell resolution of about 4 km. Data were rendered homogeneous with respect to the  
347 different satellites, which allowed data aggregation on a daily basis with the quality levels provided.  
348 Given the volume of missing or low-quality data for the study area, we aggregated data into  
349 rectangular grid boxes spanning 33' in latitude and 30' in longitude (i.e., 61x38 km), an area roughly  
350 the size of the SPM archipelago and its coastal waters. SST data with quality indices between 5 and 7  
351 (the maximum quality) were extracted and spatially averaged. Given the significant cloud cover in this  
352 region, the month offering the minimal amount of missing data was August and the ratio of clear pixels  
353 to total available did not exceed 0.20 (Fig. A1). All analyses were thus performed using August-  
354 averaged SSTs over the 37-year time series (August 1982-August 2018). The reliability of the dataset  
355 was tested by comparing it with the only long-term *in situ* measurement series available (Station 27,  
356 e.g., Drinkwater et al., 2013). The results were found to be sufficiently convincing (Fig. A2) for further  
357 analysis of this spatially aggregated dataset.

358

#### 359            4.3.2. Extraction of the nodal cycle in the sea surface temperature time series at Saint-Pierre 360 and Miquelon

361            An SST time series from the grid box including SPM (location on Fig. 1) was extracted and  
362 analyzed using EMD methods and a simple least square method (LSM) to highlight a potential nearly  
363 bidecadal cycle from SST. This analysis was challenging due to the limited length of the time series,  
364 which could only represent two cycles at best. Unlike LSM, which consists in fitting a sine function of  
365 18.6-year period on the time series, EMD does not make any a priori assumption on the periods of the  
366 different IMFs. The results of the two methods (Fig. 6) show similar amplitudes ( $\sim 1^\circ\text{C}$ ) and variances of  
367  $\sim 10\%$  relative to total SST variance. A slight and varying phase shift occurs between the two methods,  
368 but does not exceed 2 years. Pearson's correlation coefficients calculated for the 18NTC and SST series  
369 at 18.6-year period were significant ( $p < 0.002$ ;  $N = 37$ ) and ranged from -0.94 for LSM to -0.54 for EMD.  
370 Negative correlations indicate that years with high 18NTC (i.e., stronger diurnal tidal currents)  
371 correspond to greater vertical mixing and therefore lower SST around SPM during August when  
372 thermal stratification of the water column is most pronounced.

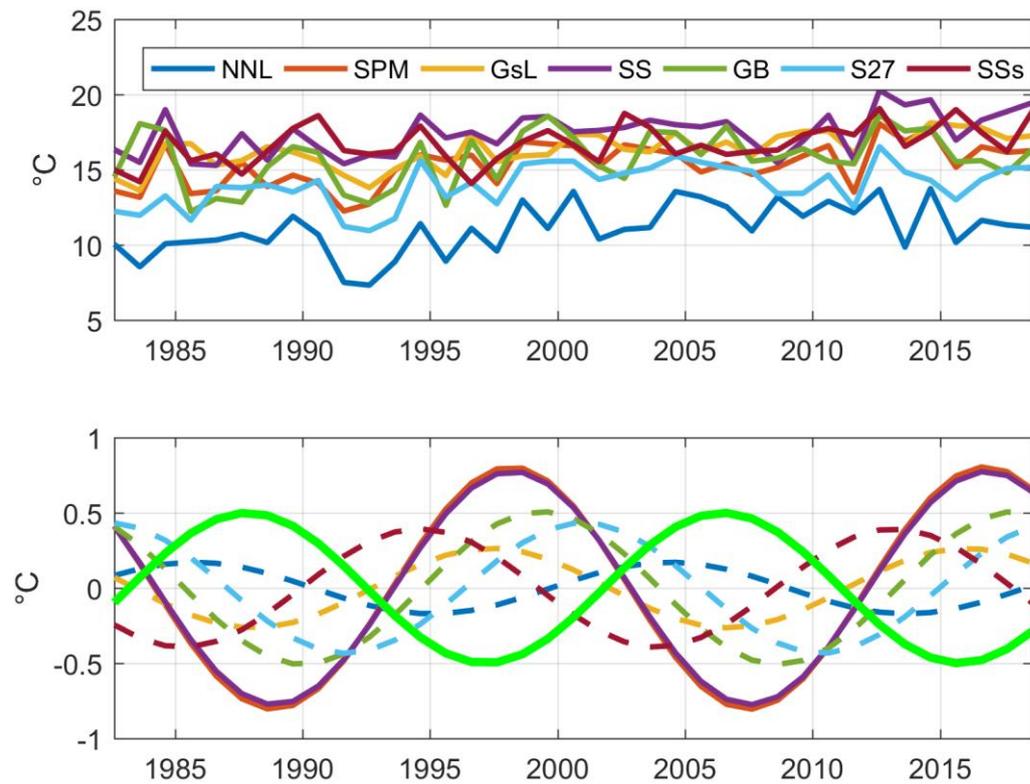


373

374 **Fig. 6.** Intrinsic mode function (IMF) time series from empirical decomposition (EMD) (blue lines) of  
 375 August satellite sea surface temperature (SST) data from Saint-Pierre and Miquelon (orange rectangle  
 376 in Fig. 1) over time. Bottom panel: SST time series (heavy black line) and residue (in blue). Panel IMF4  
 377 (second from bottom panel): 18.6-year nodal tidal cycle (18NTC) (green line), least square means (LSM)  
 378 reconstruction minus the time average (red line) and fourth IMF (blue line). The number in the upper  
 379 left corner indicates the ratio of the IMF variance to the sum of each IMF variances.

380 4.3.3 Extension to the Scotian-Newfoundland shelves

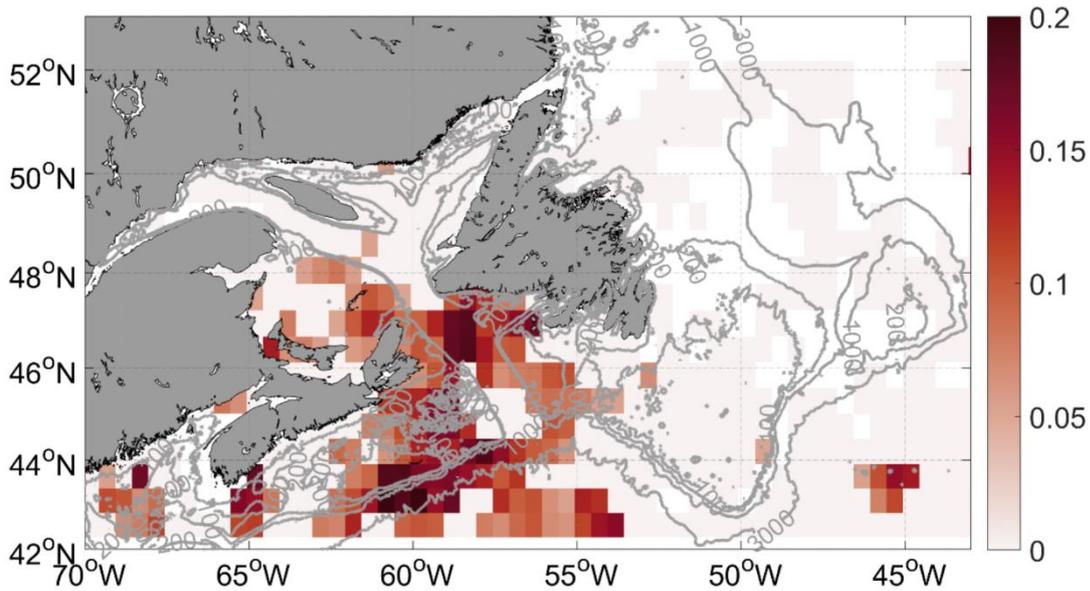
381 Taking advantage of the availability of a spatialized SST dataset and the apparent influence of  
 382 the 18NTC around SPM, we extended our exploratory SST analysis to the regional level with LSM.  
 383 Selective tests were carried out on the phase value of the fitted SST time series by comparing the  
 384 phase of the LSM series with the 18NTC phase (i.e., 67° GMT). We tested whether the LSM with  
 385 phase opposition to the 18NTC within a range of +/- 1 year (corresponding to +/-19°, i.e., 360°/18.6  
 386 yr) may be due to the 18NTC influence. Outside this range, LSM results are considered to result from  
 387 causes other than tidal mixing. As an example, several time series of August SST and the result of  
 388 their LSM compared with the 18NTC are shown in Figure 7. As expected, higher temperatures were  
 389 found south of the Scotian shelf, whereas lowest temperatures were found north of Newfoundland.  
 390 By fitting an 18.6-year period sine to these time series, the upper range of temperature variabilities  
 391 (~1°C) satisfied the phase test criterion.



392

393 **Fig. 7.** Upper panel: August satellite sea surface temperature (SST) time series extracted from the  
 394 corresponding color boxes displayed in Fig. 1. Acronyms are defined in Fig. 1 except NNL (North  
 395 Newfoundland) and SSs (South Scotian shelf). Lower panel, green curve corresponds to the 18.6-year  
 396 nodal tidal cycle (18NTC) (arbitrary amplitude of 0.5). Other curves correspond to the result of the  
 397 August SST least squares mean (LSM) minus the mean of each series. Dotted lines represent time series  
 398 which do not satisfy the phase test criterion (see text), whereas continuous lines (SPM and SS) do.

399 LSM was applied to the whole area and SST variance of grid boxes whose phase was not  
 400 between  $-132^\circ$  and  $-94^\circ$  (18NTC phase  $\pm 1$  year) was set to zero. Figure 8 displays the ratio of the  
 401 variance of the boxes satisfying the phase criterion to the variance of the SST time series. This analysis  
 402 highlights areas located near SPM to the west such as Saint-Pierre Bank, south of Magdalen Islands,  
 403 and eastern and offshore parts of the Scotian Shelf and the entrance to the Bay of Fundy.



404

405 **Fig. 8.** Ratio of satellite SST variance (color scale on the right) for Least Square Method fitted SST series  
 406 extracted from each 33' latitude and 30' longitude boxes whose phases are in opposition to the 18.6-  
 407 year nodal tidal cycle (18NTC series) by +/- 1 year. Gray lines represent 3000, 1000, 200 and 100 m  
 408 isobaths.

409 In the vicinity of the outer Laurentian Channel, part of the long-term variability of the SST is in  
 410 phase opposition with the nodal cycle. To verify that tidal mixing may be the explanatory factor, we  
 411 used a numerical model to verify the nature and magnitude of tidal currents and their contribution to  
 412 vertical mixing.

## 413 5 Numerical modeling of tidal currents

### 414 5.1 The model

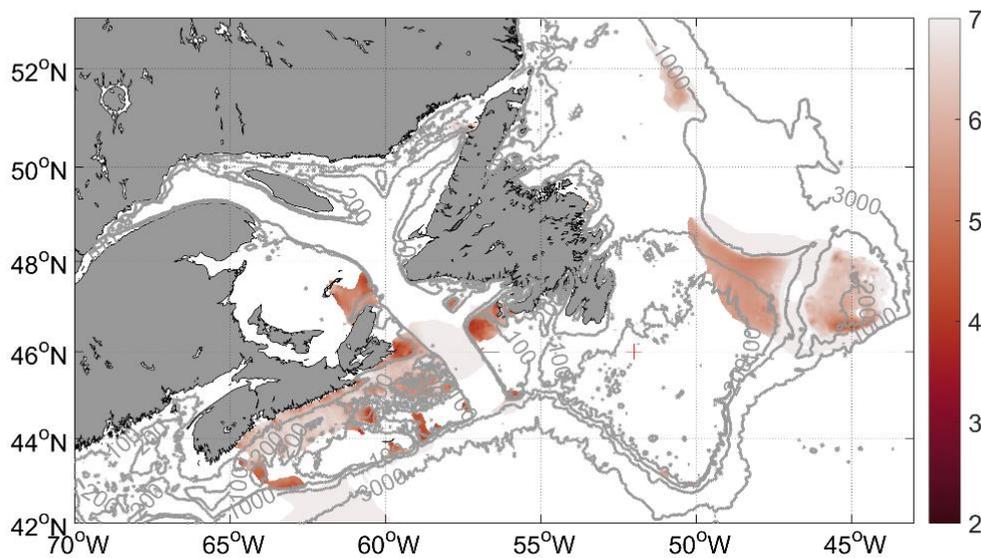
415 The MARS2D model was used to calculate barotropic tidal currents over the study area. The  
 416 model used a 2 km square grid size and was forced along open boundaries by tides extracted from the  
 417 FES 2004 database (Lyard et al., 2006). Simulations ran from 2014/01/01 to 2014/03/16 with a spin-up  
 418 of 0.5 months and have been shown to accurately reproduce tidal sea levels and currents (Bezaud et  
 419 al., 2020). The barotropic tidal currents were passband filtered (5<sup>th</sup> order Butterworth filter) to extract  
 420 semi-diurnal (3-15 h) and diurnal components (18-30 h).

### 421 5.2 Tidal mixing with emphasis on the diurnal tidal current contribution

422 As first demonstrated by (Simpson and Hunter, 1974), tidal mixing by barotropic currents  
 423 depends on the action of frictional forces on the bottom, which can be quantified by the ratio of water  
 424 depth to the cube of velocity, an estimate known as the Simpson-Hunter parameter. The lower the  
 425 value of this parameter, the greater the vertical mixing. As shown by (Garrett et al., 1978), the  
 426 transition from well mixed to stratified conditions occurs when  $H/U^3 = 70 \text{ m}^2 \cdot \text{s}^{-3}$  (4.2 in log scale) with  
 427 H the total depth (m), U the tidal current ( $\text{m} \cdot \text{s}^{-1}$ ). We calculated the time-averaged value of the  
 428 Simpson-Hunter parameter from hourly simulation results over the duration of a month for both  
 429 diurnal and semi-diurnal currents. Figure 9 shows Simpson-Hunter parameters (log scale) for diurnal  
 430 currents where these do not exceed semi-diurnal ones. The calculation highlights areas where diurnal  
 431 currents predominantly generate vertical mixing, i.e. those likely to experience the most pronounced  
 432 18NTC modulation. These areas include SPM, north of the Saint-Pierre Bank, the southeastern edge of

433 the Magdalen Islands and some locations along the Scotian Shelf off Sidney Bight and along the  
434 offshore edge of the Scotian Shelf near Sable Island.

435 These areas share a number of spatial similarities with those showing a phase opposition  
436 between the bidecadal variability in SSTs and the 18NTC (Fig. 8). These similarities suggest that the  
437 lunar nodal cycle influences SST and tidally driven vertical mixing in these areas. Along the continental  
438 shelf, vertical mixing affects not only temperatures, but also nutrient concentrations and primary  
439 production at the surface and throughout the water column. Although measurements below the  
440 surface and from near-bottom areas are not available over the duration necessary to validate this  
441 assertion, we hypothesize that increased vertical mixing (during 18NTC+) would decrease SST, increase  
442 bottom temperatures and thus promote the growth of *A. islandica*. These effects could provide an  
443 explanation for the strong positive correlation between low-frequency variability in growth and the  
444 18NTC (Fig. 4).



445  
446 **Fig. 9.** Simpson-Hunter parameter (colored logarithmic scale displayed on the right) calculated over a  
447 duration of a month from diurnal currents obtained from Bezaud et al. (2020) model simulations ran  
448 from 2014/01/01 to 2014/03/16 with a spin-up of 0.5 months and shaded when its value is lower than  
449 the Simpson-Hunter parameter calculated for semi-diurnal currents obtained from the same model  
450 simulations. Gray lines represent 3000, 1000, 200 and 100 m isobaths.

## 451 6 Discussion

452 The results interpreted here derive from three different and independent datasets. These  
453 include a combined 141-year growth record from a bivalve species living in SPM coastal waters,  
454 monthly SST measurements over a 37-year period and simulations of barotropic tidal currents on a  
455 monthly time scale. The two sets of observational data allowed us to identify positive correlations  
456 between the 18NTC and *A. islandica* growth chronology (Fig. 4) and negative correlations between the  
457 18NTC and SST (Fig. 8). The schematic modeling step helped reveal a link between SST and diurnal  
458 mixing. The remarkable spatial concordance in areas showing a phase opposition between SST and  
459 18NTC and those where strong tidal diurnal mixing prevails (Fig. 9) offers strong arguments to infer the  
460 physical process involved.

461 Hydrodynamic and ecosystem variability in the NW Atlantic has been studied intensively for  
462 decades, but to our knowledge this is the first time that the influence of 18NTC has been explored  
463 (with the exception of sea level, for which the nodal cycle has long been known). Below, we discuss  
464 the limitations of our results. Our arguments in support of a significant influence of 18NTC on local and  
465 regional hydrodynamics and ecosystems can be addressed in four questions: How reliable is the  
466 detection of 18NTC in bivalve shells? How does mixing impact shell growth? Is our SST analysis  
467 relevant for estimating bottom temperature variability and can other factors explain the bidecadal  
468 variability? Is this mixing really a result of the diurnal component of the tide?

### 469 **6.1 Evaluation of the reliability of the nodal tidal footprint in the growth of *Arctica islandica***

470 The question of whether individual organisms respond uniformly to common environmental  
471 influences can be addressed by evaluating the consistency of growth signals within a population (e.g.,  
472 Douglas, 1920; Mette et al., 2016). The expressed population signal (EPS) established from  
473 contemporaneous specimens of *A. islandica* collected around SPM (ca. 25 m depth, in a ca. 400 m<sup>2</sup>  
474 area), showed highly synchronized growth patterns. In our study, EPS values exceeded 0.85, the  
475 assumed analytical threshold (Wigley et al., 1984), from 1905 to 2015 (Fig. 1D). The series inter-  
476 correlation (0.526) and mean sensitivity (0.239) were comparable to those interpreted from other  
477 bivalve, fish and tree records (e.g., Black et al., 2005; Helama et al., 2007; Poitevin et al., 2019). Growth  
478 patterns in the different shells analyzed showed good agreement. The detrending method used to  
479 remove ontological trends may however have influenced the detection of low frequency spectra from  
480 the SGI master series. We tried to limit this uncertainty by analyzing individuals of different ontological  
481 age and by using a deterministic detrending method that preserves long-term environmental signals  
482 (Marali and Schöne, 2015; Peharda et al., 2021; Schöne, 2013). Details of the general approach to  
483 detrending and potential associated biases are fully described in previous studies (Butler et al., 2010;  
484 Schöne, 2013). Thus, the inclusion of shorter series in the chronology and the preservation of medium-  
485 and low-frequency variability by any detrending method (including negative exponential) is limited in  
486 practice to wavelengths of about one-third of the average length of the time series (Butler et al., 2010).  
487 In our case this allows us to confidently investigate wavelengths shorter than ca. 25 years (as the  
488 18NTC). The present study also highlights that removal of age trends from *A. islandica* (and other  
489 bivalves) increment width chronologies remains a major challenge to fully exploit their growth records  
490 as no detrending technique is currently specifically developed for bivalve sclerochronologies (Schöne,  
491 2013). The population sampled for this study was dense (> 10 individuals.m<sup>-2</sup>), living buried in sediment  
492 (> 1 cm below the sediment surface), not heavily preyed on and not harvested or otherwise disturbed  
493 by human activity. Thus, our master chronology was interpreted to offer consistent coverage of *A.*  
494 *islandica* growth conditions in the study area.

495 The spectral methods used in this study gave similar results and each detected a subtle, but significant  
496 spectral peak with a period of about 18.6 years (Fig. 3A). Extractions of the 18.6-year period from the  
497 master series using different methods showed that *A. islandica* experiences increased growth during  
498 18NTC maxima and reduced growth during 18NTC minima (Fig. 4). However, importantly, the influence  
499 of 18NTC on *A. islandica* growth appears to have decreased since the 1990s. This decline in the  
500 influence of 18NTC can be attributed to a decrease in increment size during the last years of life of the  
501 studied animals or to the enhanced influence of other environmental forcings exacerbated by global  
502 climate change over the past 30 years. Nevertheless, evidence of an 18NTC signal in *A. islandica* shells  
503 raises the question of the ecological mechanisms involved in the link between growth and the 18NTC  
504 signal.

### 505 **6.2 Impact of tidal mixing on *A. islandica* growth**

506 Studies have shown that *A. islandica* growth depends primarily and by varying degrees on  
507 temperature and food quantity, quality and availability (Ballesta-Artero et al., 2017; Butler et al., 2010;  
508 Marali and Schöne, 2015; Mette et al., 2016). Schöne (2013), in his review, suggested that *A. islandica*

509 through endogenous rhythms can anticipate environmental changes such as ebb or neap tides and  
510 associated changes in food availability and temperature. At the ecosystem level, Witbaard et al. (2001)  
511 demonstrated the effect of tidal resuspension on benthic food quality by studying growth of three  
512 macro-benthic organisms (including *A. islandica*) from two sites from the Southern North Sea. Recent  
513 studies of infralittoral water (15 m depth) *A. islandica* paleoenvironmental records for SPM have shown  
514 that growth depends most strongly on coastal water temperature and primary production (Doré et al.,  
515 2020; Poitevin et al., 2019). These studies however analyzed shells that developed in a practically  
516 homogeneous vertical (Fig. 5C) water column and noteworthily these shells did not experience  
517 variability with an 18.6-year period (Fig. 3B). At the circalittoral sampling site in the present study,  
518 temperature data from the end of summer showed strong vertical temperature stratification and  
519 considerable variation on time scales of a few hours (Fig. 5B). Variation in vertical temperature  
520 structure can strongly affect primary production. Although *in situ* measurements on primary  
521 production in the water column or near bottom are not available, the general dynamics described  
522 above have been observed and likely operate in comparable environments. Tides represent one of the  
523 dominant physical processes causing vertical mixing on continental shelves (e.g. Sharples, 2008). A  
524 recent study of a mid-latitude area with seasonal stratification and moderate tidal currents similar to  
525 those observed around SPM (Zhao et al., 2019) found that tidal forcing replenishes nutrients in the  
526 upper part of stratified water columns during the summer and thereby both sustains and increases  
527 primary production in the surface layer and within the pycnocline. This study and others like it have  
528 revealed consistent patterns of variability between primary production and spring-neap tidal cycles  
529 (with periods of ~14 days). Spring tides increase mixing and thus cause an increase in primary  
530 production and bivalve food availability during stratified period, as long as the turbidity induced by  
531 sediment resuspension does not constrain productivity by limiting light transmission (e.g., McSweeney  
532 et al., 2017). These tidally driven ecological mechanisms occurring in summer are very likely to  
533 influence *A. islandica* growth as, although we have not conducted specific intra-annual growth studies  
534 in SPM (given the limited access to this study site), Schöne et al. (2005) demonstrated that *A. islandica*  
535 shell collected from the southern and central North Sea reach maximum daily growth rates in August.

536 Other mechanisms could also explain the 18NTC effect on *A. islandica* growth. Those lie on sediment  
537 water interface circulation and the effect of tidal currents on the sorting of sediment and/or food  
538 particles, which could possibly influence their quality and bio-availability for *A. islandica*. These tidally  
539 driven mechanisms have previously been suggested by Witbaard et al. (2001) which demonstrated  
540 their interacting effects on food quality, resuspension, aggregate formation and sediment type to  
541 explain *A. islandica* growth variability in the southern North Sea. However, the absence of such  
542 sediment water interface environmental measurements in SPM does not allow us to further  
543 investigate these aspects in the present study.

544 Tidal mixing in regions like SPM where diurnal components dominate tidal currents can influence  
545 primary production and primary consumer growth due to the ecosystem's sensitivity to changes in  
546 tidal current speeds. Moreover, sediment characteristics limit resuspension around SPM (Robin, 2007).  
547 Thus, the subtle changes induced by the 18NTC may contribute to the strong positive correlations  
548 observed between reconstructed *A. islandica* growth patterns and the nodal tidal cycle. The observed  
549 patterns are also very consistent with the infralittoral SGI analysis, which does not display a spectral  
550 peak at the 18NTC period, because the spring-neap tide cycle has only a weak influence on ecosystems  
551 in almost vertically homogeneous shallow waters.

### 552 **6.3. Are other processes at play?**

#### 553 6.3.1 Temperature analysis

554 In this region of the Atlantic Ocean, the only reliable and continuous coastal data available over  
555 several decades (in addition to sea level records at tide gauges) are the satellite SST. We are aware  
556 that this parameter is a poor descriptor of the bottom temperatures because it also incorporates

557 advection due to general circulation and variability of ocean-atmosphere exchanges that can mask the  
558 effects of vertical mixing. We chose to use only best quality gridded products. This choice strongly  
559 constrained the spatial and the temporal resolution of the analysis because we had to perform spatial  
560 averaging and only the month of August proved to be usable. Fortunately, this month corresponds to  
561 the month when the stratification is maximal and the effect of 18NTC is potentially the most visible.  
562 Note that we did not employ the OISST database (Reynolds et al., 2007), which consists of filling the  
563 gap by assimilating *in situ* data. The results of the assimilation process vary according to the available  
564 data, which are very variable in time and space. It is therefore difficult to estimate their reliability at  
565 fine spatial scales. Analyses with this dataset nevertheless yielded roughly the same results (not  
566 shown).

567 It was tempting to use other datasets that have direct measures of bottom temperature, rather  
568 than inferring it from the SST. However, we rejected these datasets for several reasons. Databases  
569 such as EN4 (Good et al., 2013) were excluded due to their low spatial resolution and their poor  
570 consideration of continental shelves. Another alternative would have been to analyze hindcasts, i.e.  
571 model results with assimilation of observations (satellite SST, SSH, *in situ* observations), the main  
572 problem is that the models considered do not explicitly treat tides. For example, Simple Ocean Data  
573 Assimilation 3 (SODA3) (Carton et al., 2018) parameterizes tidal mixing over shelves, but ignores its  
574 diurnal components and the nodal cycle. GLORYS (Lellouche et al., 2018), based on the NEMO model,  
575 does not take tides on the continental shelves into account. The ability of the assimilation process to  
576 correct this bias depends on the density of observations, which is highly variable in space and time.  
577 Moreover, in the case of bottom temperatures, only *in situ* measurements (the rarest) are likely to  
578 correct these biases. As an example, GLORYS data in the Mid-Atlantic Bight (south of our study area),  
579 although very close to reality in general, show the largest errors over Georges Bank (Chen et al., 2021),  
580 an iconic area known for its frontal dynamics related to tidal mixing (semi-diurnal in this case) (e.g.,  
581 Guida et al., 2013). The hindcast shows (Chen et al., 2021, their Figure S2) surface temperatures that  
582 are too warm and, conversely, bottom temperatures that are too cold at monthly and at interannual  
583 time scales. These discrepancies clearly indicate an underestimation of mixing that data assimilation  
584 — although numerous in this well-studied area — fails to correct. Therefore, our SST analysis is based  
585 solely on observations, because using any of the datasets described above would not have led to a  
586 robust conclusion whatever the outcome, given their biases.

587 However, to draw robust conclusions on bottom temperature variability, we must show that  
588 other physical processes are unlikely to be involved on bidecadal time scales.

### 589 6.3.2 Have bidecadal cycles ever been suspected or observed in the study area?

590 Considerable scientific literature is devoted to describing circulation and hydrology on the NW  
591 Atlantic shelf and slope on seasonal to multidecadal time scales. The hydrology and dynamics of this  
592 region are particularly complex given that it is the meeting site of the Labrador Current and the Gulf  
593 Stream. For example, (Nigam et al., 2018) showed the importance of decadal variability, which results  
594 from low frequency variability of the atmospheric North Atlantic Oscillation (NAO). (Wolfe et al., 2019)  
595 reviewed the time scales involved in Gulf Stream fluctuations. They range from 7.5 to 13 years. It  
596 appears that the north-south migration of the Gulf Stream has a dominant period of 9 years, which  
597 could partly explain the peaks observed with a 10-year period on the growth of *A. islandica* in the  
598 spectra of the two series (Fig. 3). This study is very consistent with the results of (Poitevin et al., 2019)  
599 that show a strong correlation between *A. islandica* growth and the latitudinal position of the shelf-  
600 slope front. Moreover, (Halfar et al., 2011) also found decadal periods in coralline algae growth records  
601 along the eastern side of Newfoundland, which reflect the Labrador Current influence.

602 From the literature on the variability of hydrology in the region, we did not note any  
603 observations on a bidecadal scale. Nevertheless, bidecadal sea-level cycles in the entire Atlantic Ocean  
604 (North and South) have been detected (Vianna and Menezes, 2013) in the SODA model and these

605 oscillations may be a fingerprint of the Atlantic meridional overturning circulation (AMOC) sea-level  
606 variations, which may affect shelf dynamics. The Vianna and Menezes (2013) study reported a regime  
607 shift since the beginning of the 1970s that includes all of our SST time series. If confirmed, an AMOC-  
608 influenced cycle precludes attributing the observed bidecadal cycle to tidal dynamics. However, no  
609 influence of these cycles on coastal surface temperatures has ever been reported since the Vianna and  
610 Menezes (2013) study, and it is unlikely that the phase of these oscillations varies across the regional  
611 scale (from the Scotian shelf to Labrador shelf) due to the basin-wide scale considered in this study.

#### 612 **6.4 Diurnal tidal mixing on the Northwest Atlantic shelf**

613 The role of diurnal tidal currents in this region has not been extensively studied, probably  
614 because the semi-diurnal tidal range dominates throughout the region (with the exception of the Gulf  
615 of St. Lawrence, in which an M2 amphidromic point occurs). These currents can potentially be more  
616 important than the ratio of semi-diurnal tidal amplitudes to diurnal components would suggest. The  
617 diurnal waves are subinertial (periods (24-26 h) > inertial period $\approx$ 17 h) and the diurnal waves take on  
618 features of a coastal trapped wave that results in local current amplifications generally near steep  
619 slopes. Indeed, some strong diurnal tidal currents have been described at the edge of the Scotian and  
620 Newfoundland shelves (Ohashi et al., 2009; Xu and Loder, 2004, respectively) and more locally near  
621 Sable Island (Greenan et al., 2014) or SPM (Lazure et al., 2018).

622 A recent study (Wang et al., 2020) investigated the impact of tidal mixing in the NW Atlantic  
623 shelf using 3D numerical modeling. This study consisted in simulating circulation and hydrology with  
624 realistic forcing by comparing the results with or without taking into account the tides represented by  
625 the five major constituents (M2, N2, S2, K1 and O1). As expected, the non-tidal simulations showed  
626 higher SSTs and lower surface salinities for the month of August due to lower vertical mixing.  
627 Examination of the different terms that are at stake in temperature variability, including horizontal  
628 advection, showed that bottom temperatures depend locally on vertical diffusion (their Figure 17I).  
629 Interestingly, the areas where this mixing had the most impact broadly coincided with the areas we  
630 highlight in Figure 9. Unfortunately, the authors considered the tide as a whole and did not attempt to  
631 distinguish the effects of the semi-diurnal and diurnal components. However, the earlier work of (Han  
632 and Loder, 2003) had already noted that the diurnal K1 currents in the NW Scotian shelf were amplified  
633 by the resonance of the first-mode continental shelf wave. They suggested that vertical mixing in this  
634 area is probably mainly influenced by diurnal currents, because the O1 wave (of the same amplitude  
635 as K1 in this area) had not been considered in their study.

636 However, a barotropic model has its own limitations, because it does not take into account  
637 stratification and associated baroclinic currents. Barotropic tidal interaction with steep bathymetry in  
638 a stratified environment during the summer results in internal waves. Waves having diurnal periods  
639 are subinertial and therefore trapped by bathymetry (e.g., Huthnance, 1978). They propagate  
640 alongshore leaving the coast on their right in the northern hemisphere. The temperature  
641 measurements shown for Saint-Pierre Bank (Fig 5A) suggest strong internal dynamics, which most  
642 likely indicate a coastal trapped wave. This coastal trapped wave strengthens the near-bottom  
643 currents, causing significant shear in the cross-shore direction and contributes to increased vertical  
644 mixing in the alongshore direction. These limitations could explain why the barotropic model does not  
645 show strong mixing in the middle of the outer Laurentian Channel (depth range: 200-400 m), while the  
646 SST analysis shows strong bi-decadal variability at 46-47°N latitude.

647 As a result, the areas that we designate as being under the dominant influence of diurnal  
648 mixing are in good agreement with the above-cited papers and their extent is probably underestimated  
649 due to the limitations of the barotropic approach. The transfer of time scale from diurnal tide to nodal  
650 cycle is based on the stronger theoretical modulation of the diurnal vs. semi-diurnal components (see  
651 above). Noteworthy, this modulation is globally verified by observations (Cherniawsky et al., 2010),  
652 even though there are small observed deviations from the theory that are not yet fully understood.

## 653 **6.5 Concluding remarks**

654 Based on the annual growth lines of a large and consistent sample of *A. islandica* shells (21  
655 individuals) at SPM, we highlighted here the footprint of an 18.6-year cycle that accounts for about  
656 10% of the interannual variance in growth. We showed that this oscillation is in phase with the lunar  
657 nodal cycle (18NTC). From this observation, which is to our knowledge the first one made based on  
658 hard parts of animals, we developed an argument to explain the chain of interactions between tidal  
659 potential and bivalve growth on the sea bottom.

660 Based on previous studies of 18NTC, we hypothesized that diurnal tide-induced mixing is also  
661 the process underlying these observations on the NW Atlantic shelf. Examination of the August SSTs  
662 over 37 years and the use of a numerical tidal model led us to suggest that beyond the SPM  
663 archipelago, the Laurentian Channel environment may be partly affected by 18NTC. We also point out  
664 several caveats in our arguments that result mainly from the lack of observations spanning several  
665 decades. However, the explanatory elements that we provide seem coherent and convincing.

666 To confirm (or invalidate) our results, several avenues must be explored:

667 - Since our oceanographic analysis hinges on relationships with diurnal tide-induced mixing  
668 and SST, future sclerochronological work should naturally include the second most commonly used  
669 proxy in *A. islandica* - oxygen isotope values- which more directly relate to temperature and  
670 hydrography if salinity variations are absent, as in SPM.

671 - An analysis of spatially averaged CTD (conductivity, temperature, and depth) casts on grid  
672 boxes of reduced surface area corresponding to the sectors presumed to be affected by the 18NTC.  
673 This approach is not feasible in SPM due to the paucity of available measurements, but could be  
674 attempted on the Scotian Shelf, which has been the subject of much more work over the past several  
675 decades.

676 - 3D numerical modeling, provided by a model that has already proven its ability to accurately  
677 reproduce diurnal tides and associated coastal trapped waves. Short simulations for different phases  
678 of the diurnal nodal cycle and for different summer stratifications can help quantify the modulation of  
679 diurnal mixing.

680 - Examination of other environmental archives using sclerochronology in the target areas is a  
681 natural extension of this study. Although this approach cannot provide an explanation of the chain of  
682 interactions leading to the 18NTC footprint, it may validate (or invalidate) the relatively regional nature  
683 of the influence of 18NTC on the benthic ecosystem that we describe here.

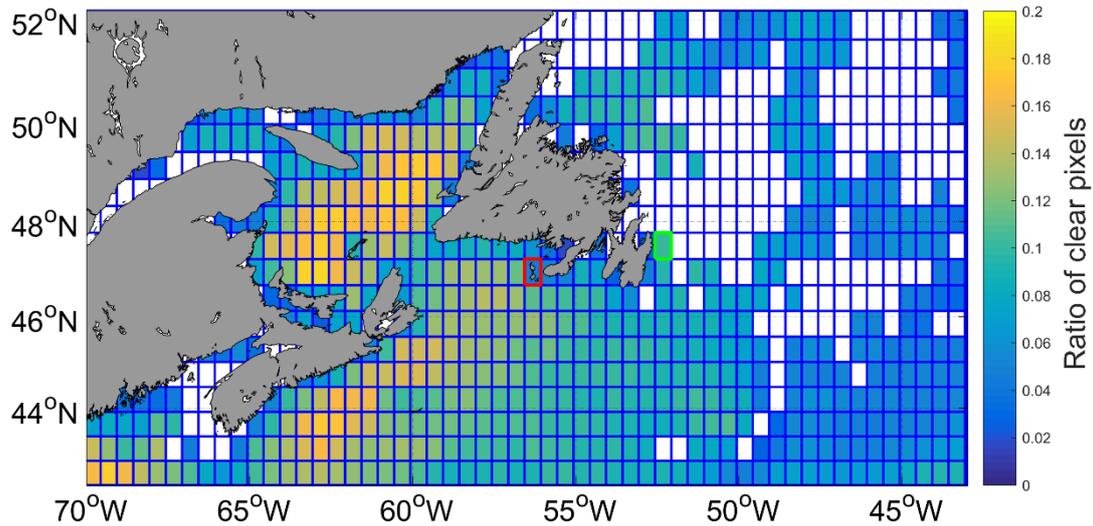
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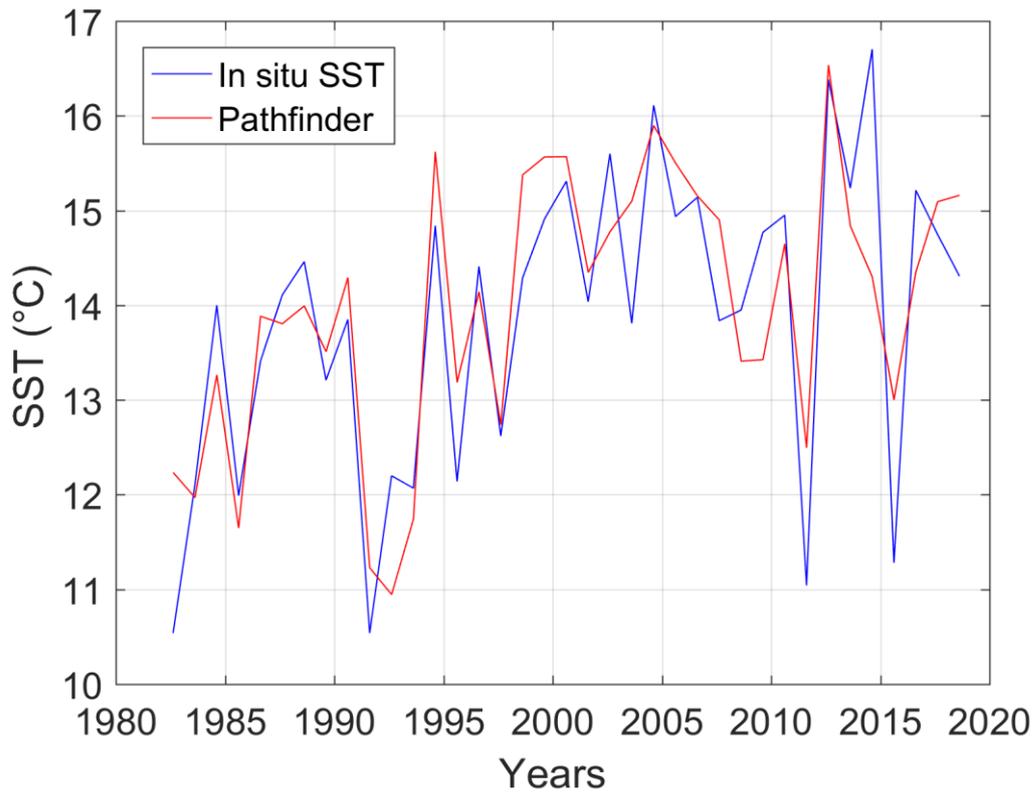
703 **APPENDIX**



704

705 **Fig. A1.** Map displaying average ratio (theoretical maximum=1) of clear pixels (quality  $\geq 5$ ) used in  
706 each grid box (33' latitude and 30' longitude including  $13 \times 12 = 156$  pixels) for Fig. 8 August satellite  
707 SST spatial analysis (Pathfinder V5.3 dataset from Saha et al. (2018)). White boxes included at least  
708 one missing year over the 37-year time series. The green-sided rectangle circles the box used to  
709 extract August satellite SST time series from around station 27 (Fig. A2). The red-sided rectangle  
710 circles the box used to extract August satellite SST time series from Saint-Pierre and Miquelon coastal  
711 water used in Fig. 6 and 7 analyses. Due to a stroboscopic effect, 4 boxes lines contain  $14 \times 12 = 168$   
712 pixels. The entire domain spans  $60 \times 23$  boxes.

713



714

715 **Fig. A2.** Comparison of *in situ* sea surface temperatures (SST) at Station 27 and spatially averaged  
 716 satellite SST from the August Pathfinder V5.3 dataset (green circled box in Fig. A1). At Station 27 (47°  
 717 33'N, 52° 35'W), monthly temperatures from surface to bottom (175 m) have been measured since  
 718 the late 1940s.

719

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