Climatic and environmental changes during the middle to late Holocene in southern South America: A sclerochronological approach using the bivalve *Retrotapes exalbidus* (Dillwyn) from the Beagle Channel

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ABSTRACT

Little is known about the effects of Holocene climate variability on marine environments and their biota in southern South America. Fossil shells of the aragonitic bivalve *Retrotapes exalbidus* (Dillwyn) offer the possibility of investigating climate variability and particularly the seasonal dynamics of sea-water temperature in the Beagle Channel during different parts of the middle to late-Holocene. We compared three specimens of different geological age (determined by ^{14}C), i.e. 5190 BP, 3839 BP, and 431 BP. These shells, respectively, refer to a cooling period at ca. 5000 BP, a climate optimum at ca. 4000 BP, and a further cooling at ca. 500 BP. All three shells showed clear annual growth bands, with a distinct intra-annual $\delta^{18}O$ cycle. $\delta^{18}O$ ranges clearly indicate higher summer temperatures in the 3839 BP shell (1.53‰—−1.16‰) compared with the 5190 BP shell (1.29‰—0.72‰) and the 431 BP shell (1.55‰—0.44‰), which correspond to maximum SSTs of 17.73 °C, 9.61 °C and 10.81 °C, respectively. Apparently, *R. exalbidus* shells are suitable bioarchives that allow comparing seasonal patterns through the Holocene, thus constituting another proxy for evaluating paleoclimatic and paleoenvironmental changes in this region.

1. Introduction

Many recent studies on reconstructing past climates are based on the isotopic composition of marine carbonates. For example, the $\delta^{18}O$ of carbonates from bivalve mollusks are used as a proxy for sea-water temperature at the time of deposition (Epstein et al., 1953). In addition, bivalve mollusks grow their shells by means of the addition of $CaCO_3$ to the shell margin and by simultaneously thickening within the pallial line (Jones et al., 2005). For a review of the value of mollusks as biogeochemical recorders of environmental and climatic conditions see Rhoads and Lutz (1980). These kinds of studies, focusing primarily upon physicochemical

variations in periodically hard tissues of organisms, fall within sclerochronology as defined by Oschmann (2009). Different studies over the last decade (e.g., Schöne et al., 2004, 2005; Watanabe et al., 2004; Carré et al., 2005; Miyaji et al., 2010; Schöne and Gillikin, 2013; among others) have shown that bivalve mollusks are valuable proxies for reconstructing environmental conditions during the Holocene, in both extant and ancient marine environments. However, most previous sclerochronological studies were located in the Northern Hemisphere, and very few published data are from southern South America.

For the Beagle Channel region there is just one recent work by Colonese et al. (2012) on stable oxygen isotope ratios in shells of an epifaunal gastropod (the limpet *Nacella deaurata*) recovered from archaeological shell middens within this area. Holocene *Retrotapes exalbidus* shells (previously included in *Eurhomalea*) are particularly suitable for investigating climate variability in the Beagle Channel and past seasonal dynamics of sea-water temperature

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during the middle to late Holocene interval. This is mainly due to two reasons: (1) *R. exalbidus* shells preserve annual increments in the outer shell layer, capturing the full seasonal temperature amplitude in the shell (Lomovasky et al., 2002; Yan et al., 2012); and (2) although not as common as other venerids, this species is also preserved in different Holocene marine outcrops along the channel (Gordillo et al., 2005; Cárdenas and Gordillo, 2009). In this study, analysis of shell growth increments (sclerochronology) and oxygen isotope measurements are used to evaluate changes in climate and seasonal variability in the Beagle Channel region, southern South America, (Fig. 1A) during the last 5000 years.

2. Regional setting

The Beagle Channel is about 200 km long and separates Tierra del Fuego, to the north, from Navarino and other smaller islands, to the south (Fig. 1B) During the Pleistocene, this drowned glacial valley was glaciated repeatedly in at least two major episodes (Rabassa et al., 1992, 2000). After the Last Glacial Maximum at ca. 25,000 BP the climate improved, beginning a phase of deglaciation with ice retreat, leaving behind proglacial lakes at ca. 16,000 BP. Marine transgression to the western Beagle Channel occurred before 8000 BP (in Lapataia Bay; Rabassa et al., 1986) leaving Holocene marine deposits, mostly raised beaches, distributed along both northern and southern Beagle Channel coasts. These deposits contain mollusk shells that were previously studied from taphonomic and paleoecological viewpoints (Gordillo, 1999; Gordillo et al., 2005, among other works).

3. Material and methods

3.1. Fossil and modern shells of Retrotapes

We analyzed fossil specimens of *R. exalbidus* recovered from marine Holocene deposits along the Beagle Channel, covering a period of around 5000 years. Specimens for dating (N = 3) were collected from the Río Ovando site (RO; Fig. 1B) and from two sites on Gable Island, a marine terrace located on the northern coast (NG; Fig. 1B), and a marine deposit located on the southern coast (SG; Fig. 1B). Modern individuals (N = 6) were sampled in Ushuaia Bay (Fig. 1B) in 3—5 m of water by SCUBA diver. In all individuals collected, we measured shell height (H, umbo to the ventral margin along the axes of maximum growth).

3.2. Geological age

A fragment of each fossil shell was used for ^{14}C dating, performed in the Poznań Radiocarbon Laboratory by the accelerator mass spectrometry (AMS) technique. Conventional radiocarbon ages were converted to calibrated ^{14}C ages by the program Calib 6.0 (Stuiver and Reimer, 1993) using the Marine09 calibration data set (Reimer et al., 2009) and assuming for the study region a local ^{14}C marine reservoir effect (ΔR) value of 221 $\pm$ 40 years.

3.3. Annual growth banding and growth rate

Individual age was inferred from internal shell growth bands following Lomovasky et al. (2002). The left valve of each specimen was coated with epoxy resin to avoid shell fracture during sectioning. Then the shell was cross-sectioned (perpendicular to the growth lines) along the axes of maximum growth in height using a low-speed precision saw (Buehler Isomet) and polished using a 2-speed grinder-polisher (Buehler Alpha) using grits of 120, 400, 600 and 1000 grade. Shell cross-sections were cleaned ultrasonically (Sonorex Super RK510). Ontogenetic age was determined by counting the annual growth increments under a stereo microscope (Olympus SZX12). In each specimen we counted growth bands in both the umbonal region and along the axis of maximum growth in order to enhance counting accuracy.

The annual shell growth increments between translucent growth bands (see Lomovasky et al., 2002) were measured for each shell. We used the Gulland and Holt (1959) plot to linearize the relationship between annual shell growth increment I_t and age t:

$$I_t = a + b*CI_t$$

where I_t is the annual growth increment in shell height at age t and CI_t is the cumulative sum of all increments up to age t. Intercept a represents maximum growth in the first year of life, whereas slope b indicates how fast growth slows down with increasing age.

A full interaction ANCOVA model (dependent variable I_t, independent variable geological age, covariate CI_t) was used to evaluate differences in growth between fossil and modern specimens when preconditions of normality, homoscedasticity and parallelism were met (Zar, 1999). To enhance overall data set homogeneity, we restricted the statistical analysis to the size range <50,000 μm CI_t.

3.4. Isotopic analyses

The right shell valve of each specimen was used to collect carbonate samples for stable isotope analysis. Shell material was milled from thin sections with a rounded 150 μm-diameter drill bit on a computer programmed New Wave Research MicroMill™ at the Sclerochronology lab (Alfred Wegener Institute, Bremerhaven, Germany). Samples were collected on a transect across two or three subsequent shell growth increments. We delimited the analysis to a sector of the shell near an age of five years because *Retrotapes* shells were difficult to sample as a result of their very thin and fragile shell structure (Fig. 2). This sector was chosen after examining the 3 shells in cross section through a magnifying glass, because it was

Fig. 1. Map of the Beagle Channel (A) and the sampling sites (B). Fossil shells of the bivalve *Retrotapes exalbidus* were recovered from Holocene raised marine deposits (circles in 1B) located along the Beagle Channel. Living specimens were sampled in Ushuaia Bay (square). See geological background in Gordillo et al. (2005). RO: Río Ovando site. NG: site at northern Gable Island coast. SG: site at southern Gable Island coast.
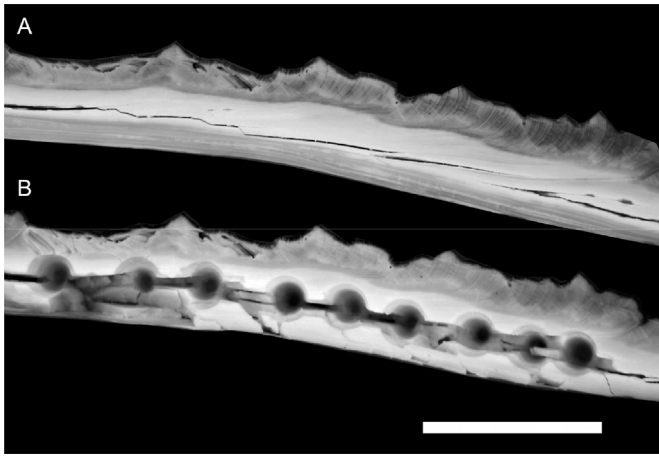
Fig. 2. Cross section of a sector of a fossil *Retrotapes* shell before (A) and after (B) sampling. Drill holes are 150 μm diameter × 250 μm depth.

the best preserved in the cross sections. Each sample yielded 50—120 μg of carbonate powder for isotopic analysis.

Oxygen isotopes were determined in the stable isotope laboratory of the Alfred Wegener Institute with a Finnigan MAT251 mass spectrometer coupled to an automatic carbonate preparation device. The results were reported in δ-notation compared with the VPDB (Vienna Pee Dee belemnite) standard calibrated via NIST19 (National Institute of Standards and Technology isotopic reference material 19). The precision of measurements was better than ±0.08‰ for $\delta^{18}O$ based on repeated analysis of a laboratory working standard over a one-year period.

3.5. Paleotemperatures

For the reconstruction of paleotemperatures for each geological age from shell oxygen isotopes we used the paleotemperature equation for aragonite given by Grossman and Ku (1986), taking into account sea surface temperature (SST) and salinity (PSU) at the Beagle Channel. SST was obtained from instrumental records at different stations along the Beagle Channel, covering a period of approximately 50 years from 1963 to 2011.

The Grossman and Ku (1986) equation is based on the principle introduced by Epstein et al. (1953): T ($^{\circ}C$) = $20.6 - 4.34*(\delta^{18}O - \delta^{18}Ow)$ where T represents temperature ($^{\circ}C$) and $\delta^{18}O$ and $\delta^{18}Ow$ refer to carbonate sample and water $^{18}O/^{16}O$ isotope ratios, respectively. $\delta^{18}Ow$ is expressed as the deviation from standard mean ocean water (SMOW). Here we use $\delta^{18}Ow = -1.81‰$ PDB, as determined by Obelic et al. (1998) in Ushuaia Bay (salinity around 30 PSU).

For the same purpose, to estimate changes in paleotemperatures from changes in $\delta^{18}O$ of water, average oxygen isotope values of *Retrotapes* shell carbonate for each geological age were plotted as the difference between modern and fossil isotopic values; i.e., zero indicates that there is no difference between modern and paleontological data. If the difference has a negative value it is interpreted as a $\delta^{18}O$ diminution of water, presumably resulting from an increase in temperature.

4. Results

4.1. Geological age

Radiocarbon data for the three fossil specimens showed that specimen R1 from the Río Ovando site at the Cormoranes Archipelago yielded an age of 4100 ± 35 yr BP. Specimen R3 from the

southern coast of Gable Island yielded the youngest age (1050 ± 35), and specimen R4 from the northern coast of Gable Island yielded the oldest age (5120 ± 35). The corresponding calibrated ages are 3839, 431 and 5190 BP, respectively (Table 1).

4.2. Annual growth banding and growth rate

The 3839 BP *R. exalbidus* specimen was 14 years old. The specimen of 431 BP was 8 years old and the specimen of 5190 BP was 10 years old (Table 1, Fig. 3).

The shell cross-sections of the three fossil specimens showed distinct growth bands (Fig. 4) as also found in recent shells (see Lomovasky et al., 2002). The slope of the relationship between the growth increment width and their cumulative size (Gulland and Hold plot) differed significantly between the four data sets (Interaction ANCOVA, F = 191.49, p < 0.0001; Fig. 4). The higher slope in the specimen dated at 3839 BP indicates a greater difference in the change of growth rate over time than in Modern, 431 BP and 5190 BP specimens respectively (Table 2). A higher initial growth rate (increment width) was found in the individual dated at 3839 BP than Modern and 431 and than 5190 BP.

4.3. Isotopic analyses

In the specimen with an age of 3839 BP, $\delta^{18}O$ values ranged from 1.53‰ to −1.16‰. The second specimen with an age of 431 BP yielded $\delta^{18}O$ values from 1.55‰ to 0.44‰. The specimen with an age of 5190 BP yielded $\delta^{18}O$ values from 1.29‰ to 0.72‰. We correlate the most positive $\delta^{18}O$ values with winter and the most negative $\delta^{18}O$ with summer (Fig. 3). Accordingly, summer values around 3839 yr BP were more negative than around 5190 years or 431 BP. $\delta^{18}O$ mean values for each shell were summarized in Table 1.

In both the 431 BP and the 5190 BP shells, isotopic values show slight differences between minimum values for 2—3 consecutive years (Fig. 3F and I, respectively), which were not observed in the 3839 BP shell. In the 3839 BP specimen the minimum values for 2 consecutive years were similar (Fig. 3C).

4.4. Paleotemperature

Using SST data collected between 1963 and 2001 (Servicio de Información Ambiental y Geográfica, CADIC-CONICET) and between 2005 and 2011 (Juan Fosati, personal communication to SG) we generated Fig. 5. Based on these data and PSU values obtained from different sources (Iturraspe et al., 1989; Obelic et al., 1998; Colonese et al., 2012) we correlated SST with salinity (Fig. 6).

Table 1
Mean radiocarbon corrected age, ontogenetic age and oxygen isotope values of the three fossil shells selected.

Samples	R1	R3	R4
Radiocarbon date	4100 ± 35 (Poz45293)	1050 ± 35 (Poz45121)	5120 ± 35 (Poz45122)
Mean value (corrected age)	3839	431	5190
Delta R (reservoir effect)	221 ± 40		
Ontogenetic age	14	8	10
Oxygen isotopes			
N	18	15	9
Max	1.53	1.55	1.29
Min	−1.16	0.44	0.72
Mean	0.01	0.91	1.01
Intrashell variability (Δ)	2.69	1.11	0.57

N: number of oxygen isotopes samples. Max: maximum oxygen isotope value. Min: minimum oxygen isotope value. Mean: mean oxygen isotope value.
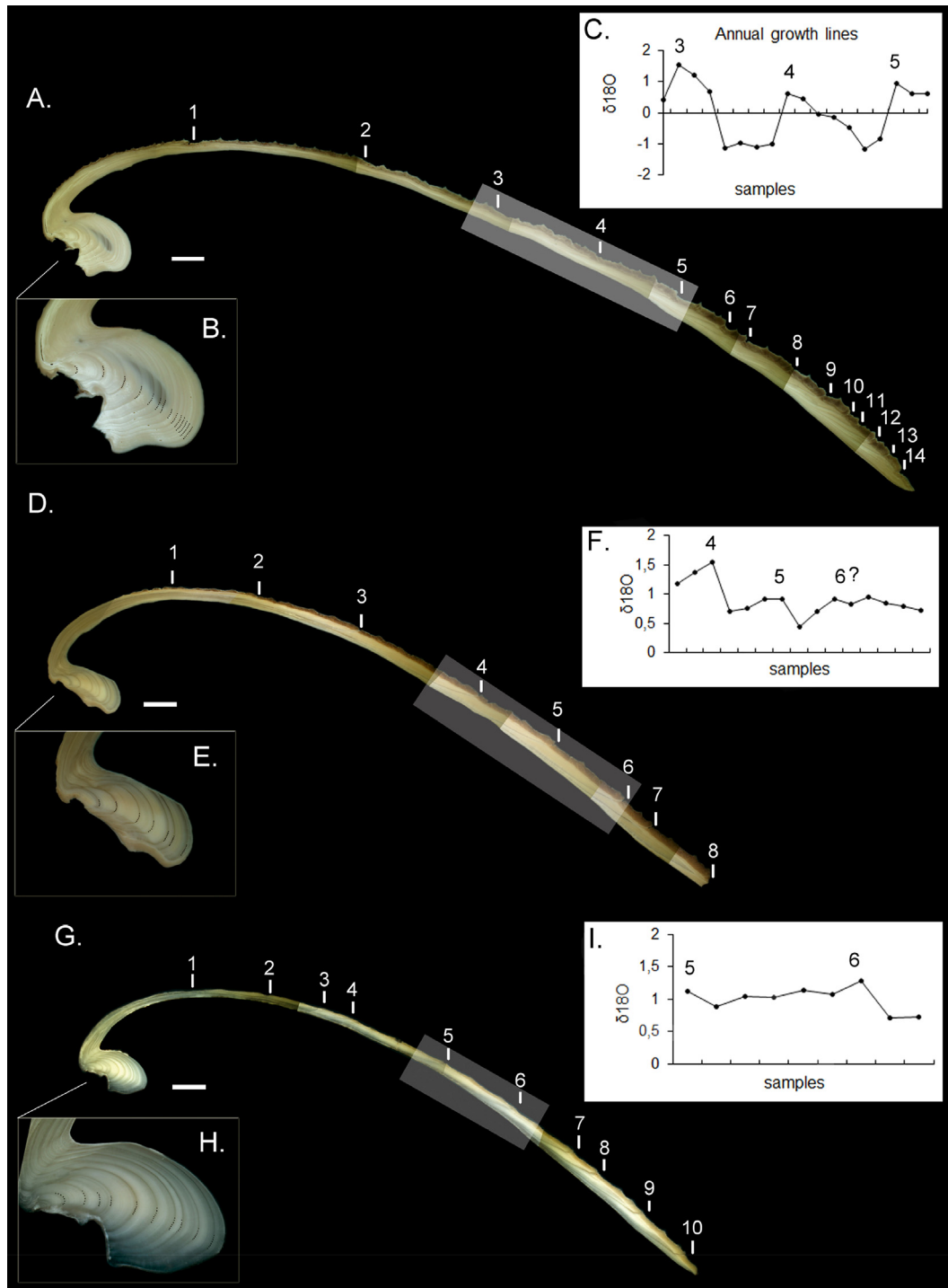
Fig. 3. Cross-sections showing annual growth banding and oxygen isotope profiles in three fossil specimens of *Retrotapes exalbidus*. A–C. The 3839 BP specimen. D–F. The 431 BP specimen. G–I. The 5190 BP specimen. The rectangles show the area sampled for carbonate in each specimen.

To obtain the corresponding temperature estimates, we applied the paleotemperature equation for aragonite to the $\delta^{18}O$ values (Fig. 7).

The 3839 BP shell indicates both a more pronounced seasonal temperature amplitude and higher summer temperatures compared with the other shells (17.73 °C compared with 9.61 °C and 10.81 °C, respectively).

Finally, average isotopic values for each geological age were plotted as the ratio between modern and corresponding fossil isotopic values for different ages (Fig. 8). At the age of ca. 4000 BP this ratio adopts a negative value, implying $d^{18}O$ diminution of seawater, and a possible increase in temperature.

5. Discussion

We present a preliminary proxy for water temperature in the Beagle Channel to evaluate marine climatic and environmental
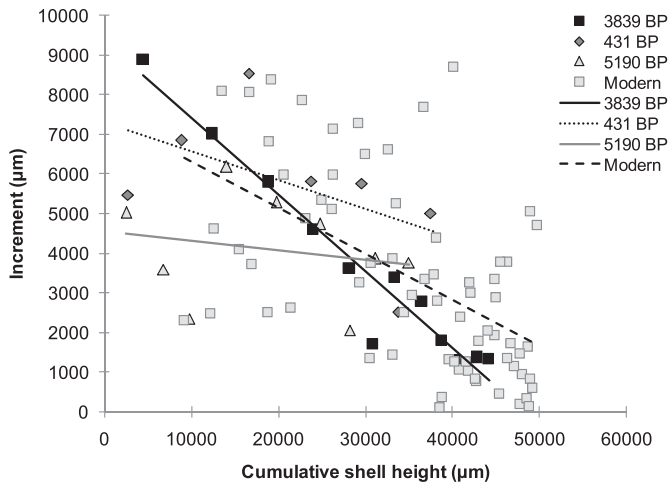
Fig. 4. Relationships between annual growth increment in shell height at age t and the cumulative sum of all increments up to age t (Gulland and Hold plot) for the three fossils (aged 431 BP, 3839 BP and 5190 BP) and six modern specimens of *Retrotapes exalbidus*.

changes during the middle to late Holocene based on sclerochronological analyses of Holocene bivalve shells.

Our results indicate that *R. exalbidus* from the Beagle Channel (54°S) captured the full seasonal temperature amplitude in its shell. A previous study performed on live-collected *R. exalbidus* specimens further north (51°S; Yan et al., 2012) showed that with increasing ontogenetic age, the discrepancy between measured and reconstructed temperatures increased exponentially. However, when this disequilibrium fractionation effect is taken into account this species can serve as a high-resolution paleoclimate archive for middle to high latitudes of southern South America, providing quantifiable temperature estimates, even from single fossil specimens. In the light of these preliminary results, future research focused on specifying to what extent these shells are formed in isotopic equilibrium with the ambient water will benefit investigations at a large spatiotemporal scale.

In order to discuss our results, it is important to note that in the Southern Hemisphere the timing and character of Holocene climate changes varies considerably from place to place, indicating that it is a combination of global and regional/local events. In this regard, in southern South America changes in Holocene climate over multimillennial scales seem to be associated with shifts of the Southern Westerlies (atmospheric changes) coupled with the Antarctic Circumpolar Current (ACC, oceanographic changes) (Lamy et al., 2010; Fletcher and Moreno, 2011). However, the pattern of short-term climate variability (i.e., multicentennial-to millennial-scale) is more complex, especially after 5000 BP, as variations do not exactly match shifts of the Southern Westerlies, and even have been linked to the onset of the modern state of the ENSO (Lamy

Table 2
Relationships between annual increment in shell height at age t (I_t) and the cumulative sum of all increments up to age t (CI_t) as described by linear regression **y** = a + b**x** for the three fossils (aged 431 BP, 3839 BP and 5190 BP) and six modern specimens of *R. exalbidus*.

Variable X	Variable Y	Specimen	a	b	r^2
CI_t	I_t	5190	4560	−0.024	0.05
		3839	9362	−0.194	0.95
		431	7293	−0.072	0.27
		Modern	7457	−0.116	0.31

et al., 2002; Lamy and de Pol-Holz, 2013). In addition, topographical and bathymerical settings of the Beagle Channel result in complex local oceanographic conditions characterized by at least five different interacting water masses (Sievers and Silva, 2008). Furthermore, the exchange flows in the Patagonian fjords, which are connected to the open ocean only indirectly, appear to be strongly modulated by local, channelized winds and to be strongly influenced by the fresh water discharged from neighboring glaciers (Moffat, 2014).

The lack of high-resolution analyses in relation to Holocene climatic changes in the Beagle Channel makes interpretations of paleotemperatures still speculative in nature. However, both marine and continental proxies (Obelic et al., 1998; Grill et al., 2002; Strelin et al., 2008) provide some evidence that during the mid-Holocene (~7000−3800 BP) to the present, climate varied in the channel.

5.1. The 5190 BP shell

This *R. exalbidus* specimen lived during a phase of climatic deterioration of unclear origins that took place in the Beagle Channel region between 6.5 and 5 ka BP (Obelic et al., 1998; Grill et al., 2002). Obelic et al. (1998) concluded from carbonate shell isotopic data that at ca. 6000 ^{14}C BP the seawater temperature of the Beagle Channel was 1.5 °C below the present value. Later, Strelin et al. (2008) recognized a neoglacial advance between 6000 and 5000 BP, during which the glaciers deposited external moraines in the Monte Sarmiento Massif and, further east, in the Cordillera Fueguina Oriental region. This cooling probably traces the advection of subpolar water by the ACC (Lamy et al., 2001, 2002; Lamy and Kaiser, 2009).

5.2. The 3839 BP shell

This shell showed the most distinct seasonal temperature amplitude and the highest summer temperatures. Its geological age relates to it lived during a regional climatic optimum phase during the mid-Holocene. Renssen et al. (2005) simulated a coupled atmosphere-sea ice-ocean-vegetation model in the high latitude Southern Hemisphere and found a thermal optimum in the 6000−3000 BP window with temperatures locally 3 C° above the pre-industrial mean. In the western Antarctica Peninsula, mid-Holocene local climate evolved towards slightly colder conditions, but a brief period of warming between ca. 4200 and 3100 BP was also recognized (Etourneau et al., 2013). In James Ross Island, Antarctic Peninsula., this warming occurred between 3900 and 3000 BP (Strelin et al., 2005). For the Beagle Channel, this climate optimum seems to have taken place between ca. 4500 and 3000 BP, according to charcoal dating and isotopic data on mollusk shells from archeological sites (Piana, 1984; Obelic et al., 1998). One explanation for this period of climatic amelioration could be linked to changes in the position of the westerly wind belt (so-called Southern Westerlies) between the Antarctic Peninsula and southern South America during the mid-Holocene, which has long been debated and remains controversial and unclear (Lamy et al., 2010; Etourneau et al., 2013). Beyond this origin, a strong seasonality and oceanographic changes appeared to affect the phytoplankton biomass, which could be reflected in the higher growth rate of the 3839 BP specimen. Changes in productivity could be related to latitudinal shifts of the ACC combined with a higher input of terrestrial micronutrients (Lamy et al., 2002). Although this climatic amelioration could result in a decrease of ocean productivity, given the proximity of the Beagle Channel waters to land, an increase in precipitation and fresh water discharge (Gordillo et al., 1993; Candel et al., 2009; Candel and Borromei, 2013) will result in an
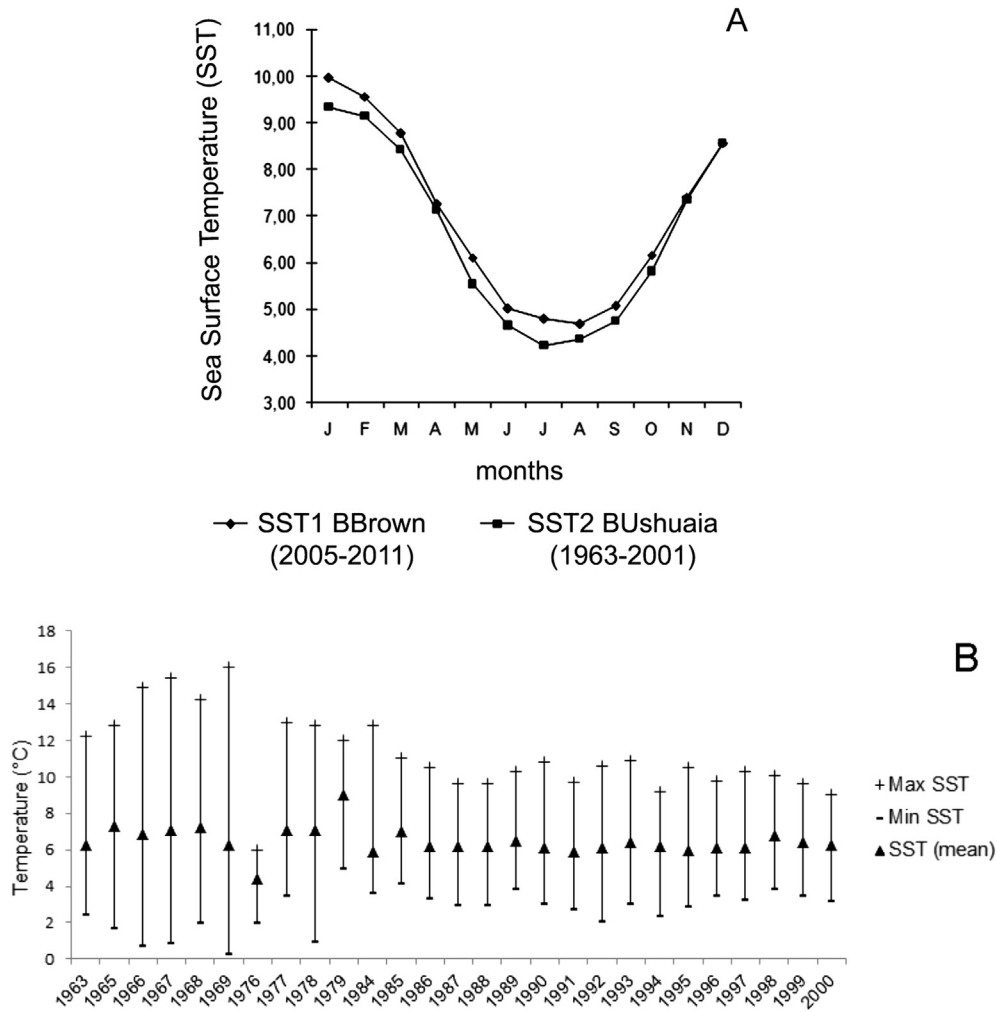
Fig. 5. Sea surface temperature (SST) in the Beagle Channel. A. Monthly (mean value) sea surface temperature (SST) from the Beagle Channel over a period of approximately 50 years. SST1: data from Brown Bay. SST2: data form Ushuaia Bay. B. Annual (mean value) SST and maximum and minimum values between 1963 and 2000 obtained from the Muelle Orión site in Ushuaia Bay. Data source is mentioned in the text.
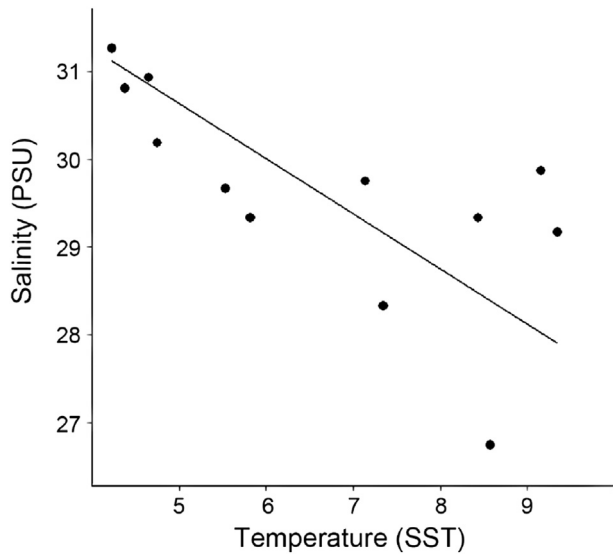
increase in productivity associated with the input of terrestrial debris. This reasoning explains why the 3839 BP shell may have developed under warmer conditions and higher productivity than the other specimens analysed.
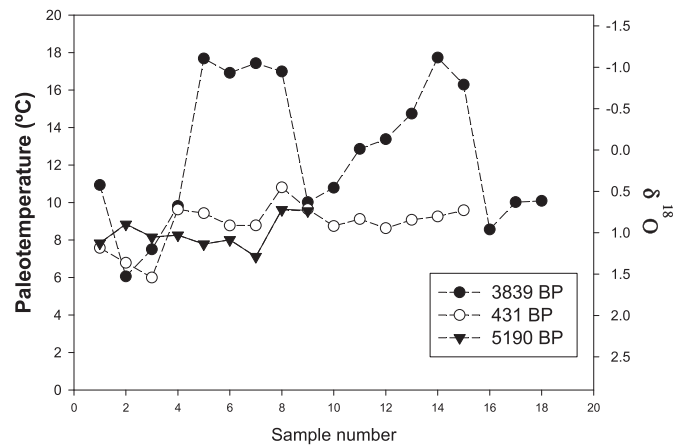

Fig. 6. Correlation ($r^2 = 0.45$; $P = 0.016$) and linear regression ($y = -0.633x + 33.798$) between sea surface temperature (SST) and salinity (PSU) in the Beagle Channel. Data source is mentioned in the text.

Fig. 7. Paleo water-temperature (left axis) estimated by the paleotemperature equation for aragonite shells and oxygen isotope values (right axis) of Holocene specimens of different age (3839, 431 and 5120 BP).
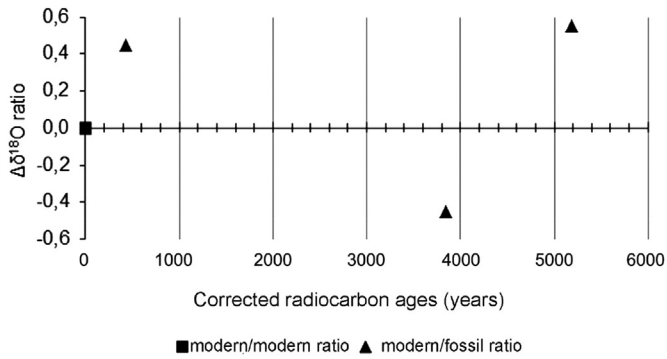
Fig. 8. Trends through time based on oxygen isotopic values in fossil specimens of *Retrotapes exalbidus*. Each triangle in the graph represents the difference between the oxygen isotopic values of a living and a fossil specimen at a different ^{14}C age. The square (modern/modern ratio) is zero.

5.3. The 431 BP shell

This shell lies within the so-called Little Ice Age (LIA). But also, within the LIA, the 450 BP (1500 AD) age coincides with the Spörer Minimum, a 90-year span of low solar activity, from about 1460 until 1550 AD (Eddy, 1976). The LIA was a 500-year climate event of cooling, which occurred from about 1300 to 1800 AD. This cooling was apparently a global phenomenon, but has been studied more intensely in the Northern Hemisphere. In southern South America, tree-ring data from Patagonia show cold episodes between 1270 and 1380 AD and from 1520 to 1670 AD, periods contemporary with LIA events in the Northern Hemisphere (Villalba, 1990, 1994). More recently, in a multiproxy study performed on lacustrine sediments at Lago Frías, in northern Patagonia, Ariztegui et al. (2007) showed that the LIA can be linked directly to changes in climate. However, this cooling is partly attributed to the solar cycles and the Tropical Atlantic Sea Surface Dipole (TAD), and partly reflects a dominant El Niño/Southern Oscillation (ENSO) signal.

Many glaciers of Tierra del Fuego and south Patagonia responded to the LIA cooling between 400 and 100 yr BP (Clapperton and Sugden, 1988; Strelin et al., 2008). This event was also clearly recorded by the seawater temperature proxy (Obelic et al., 1998).

In addition, the 450 BP shell clearly showed intra-shell variations of the lowest annual values, denoting seasonal changes between two consecutive years, and consequently demonstrating climatic instability at the very short scale of two years. The analysis of longer transects, i.e. covering much longer periods of $\geq$20 years of shell growth, might help to evaluate whether the seasonal variability observed here is related to El Niño Southern Oscillation (ENSO), a major source for global climate variability on interannual timescales (Lamy and de Pol-Holz, 2013) and which was also recorded for the Beagle Channel (Brey et al., 2010).

6. Final remarks

This sclerochronological study based on a same of a bivalve species (*R. exalbidus*) at four different Holocene ages within one environment, the Beagle Channel, demonstrates the potential of this species for (a) the analysis of annual growth banding to compare individual growth patterns and (b) the analysis of sub-annual variability in δ^{18}O and thus the seasonal resolution of the temperature signal. In this regard this preliminary analysis demonstrated short-term environmental and climate changes within the mid-Holocene and the present interval, which are partly due to global-to regional-scale events, but partly, also have local causes.

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