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Oceanographic control on shell growth of *Arctica islandica* (Bivalvia) in surface waters of Northeast Iceland — Implications for paleoclimate reconstructions

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ABSTRACT

Absolutely dated, annually resolved sea surface temperature records from middle to higher latitudes covering long time intervals are crucial to better understand the climate system. Such data can potentially be obtained from variations in shell growth of long-lived bivalves such as *Arctica islandica*. This study presents the first statistically robust 178-yr long composite chronology (covering 1835–2012) based on sixteen live-collected and subfossil specimens of *A. islandica* from unpolluted, shallow waters of Northeast Iceland. Between 1875 and 1996, up to 43% of the variation in annual shell growth was explained by SST during February to September. Faster growth occurred when temperatures were warmer and food supply was elevated. However, the correlation was subject to strong temporal variations. Likewise, the inter-series correlation (synchrony among time series) was intermittently stronger and weaker. If more uniform environmental conditions prevailed over a longer time interval and the habitat was solely influenced by one of the major currents in this region – the warm, nutrient-rich Irminger Current or the cold, nutrient-poor East Iceland Current – the agreement between growth records of contemporaneous specimens broke down and the correlation between shell growth and SST was at minimum. However, when the habitat was under the alternating influence of both currents, the inter-annual variability of shell growth and synchrony in growth among the specimens were at maximum, and the correlation between SST and shell growth strengthened. As demonstrated here, the relationship between shell growth of *A. islandica* and environmental variables is highly complex and depends on oceanographic parameters. These findings should be taken into account in subsequent studies in order to reliably reconstruct SST and other environmental variables from shells of this species.

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1. Introduction

Shells of the bivalve mollusk *Arctica islandica* (Linnaeus, 1767) serve as a novel ultra high-resolution archive of paleoclimate dynamics in the upper 500 m of the boreal North Atlantic Ocean (Nicol, 1951; Jones, 1980; Schöne, 2013). Like other mollusks, this species contains distinct growth patterns in its shell consisting of annual and daily growth lines and growth increments (Jones, 1980; Thompson et al., 1980; Schöne et al., 2005a). With these growth patterns, each increment can be placed in a temporal context. If the exact date of a particular growth increment is known, e.g., the date of death, it is also possible to assign precise calendar dates to the complete shell record. Changes of ambient environmental conditions (e.g., water temperature, food availability) are recorded by the shells in the form of variable increment widths (e.g., Witbaard et al., 1997) and variable geochemical properties (e.g., Schöne et al., 2011; Wanamaker et al., 2011; Holland et al., 2014a). Since annual growth line formation, i.e., the period of retarded or halted growth, occurs during late summer/fall (Weidman et al., 1994; Witbaard et al., 1994; Schöne, 2013), shells of *A. islandica* record the full seasonal amplitude of environmental variables (Schöne et al., 2005a). What makes this species special among other sclerochronological paleoclimate archives is the extraordinary longevity of up to 500 years (Schöne et al., 2005b; Wanamaker et al., 2008; Butler et al., 2013). Individual shells can thus provide subseasonally resolved environmental information over a coherent time interval of several hundred years. Furthermore, based on synchronous changes in relative shell growth rates, it is also possible to combine increment width chronologies from specimens with overlapping life spans to build so-called composite or master chronologies covering centuries to millennia (e.g., Marchitto et al., 2000; Butler et al., 2010; Lohmann and Schöne, 2013; Holland et al., 2014b).

A number of studies successfully constructed such composite or master chronologies from specimens of *A. islandica* that lived near or below the thermocline (Marchitto et al., 2000; Schöne et al., 2003; Butler et al., 2010, 2013; Matras, 2011). For example, Marchitto et al. (2000) presented a 154-yr long chronology from Georges Bank (Gulf of Maine) using three live-collected and four dead, single shells from

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57 to 79 m water depth. Specimens used in the 1357-yr long master chronology by Butler et al. (2013) came from slightly deeper settings (81–83 m) west of Grímsey Island, Northern Iceland. However, only a few studies targeted shells of *A. islandica* specimens that dwelled in the upper few meters of the ocean (Turekian et al., 1982; Epplé et al., 2006; Stott et al., 2010). These studies found only a poor agreement between increment width series of contemporaneous specimens which complicates the construction of composite chronologies. Furthermore, the correlation between shell growth and SST (or other variables, such as the NAO as investigated by Epplé et al., 2006) was very weak or statistically non-significant. However, coherent, high-resolution and well-dated extratropical proxy SST reconstructions spanning centuries to millennia are crucial to better understand the forcings and feedbacks that operate in the climate system. This is because the uppermost ca. 20 m of the ocean are directly interacting with the overlaying atmosphere and as such control weather and climate phenomena (Wanner et al., 2001). Whereas shallow-water corals have provided coherent, seasonally and annually resolved SST proxy records for tropical settings, only a very limited number of potential SST archives with same temporal resolution are currently available for the extratropical oceans. Potential archives include coralline red algae (Halfar et al., 2007; Kamenos, 2010), cold-water corals (McCulloch et al., 2010) and shells of bivalve mollusks (Strom et al., 2005; Black et al., 2008; Brocas et al., 2013). Clearly, there is the need for additional paleoclimate archives offering extremely high temporal resolution and uninterrupted time series.

Here, we tested the hypothesis that *A. islandica* specimens from the upper, well-mixed portion of the water column (<23 m) of an unpolluted setting off Northeast Iceland can be used for high-resolution paleoclimate analyses. Specifically, we addressed the following questions: Are there synchronous changes in shell growth among specimens from surface waters permitting the construction of statistically robust composite chronologies? Which factors control changes in the coherency of shell growth among coeval specimens? How strongly are changes of annual shell growth related to sea surface temperature? Results of our study can help to better comprehend historical ocean–atmosphere interactions and past weather phenomena in the North Atlantic realm.

2. Material and methods

Eleven specimens of *A. islandica* were obtained by dredging near Lónafjörður, Langanes Peninsula, Northeast Iceland in August 2012 (Fig. 1; Table 1). The majority of samples came from 8.4 to 11.7 m water depth, and one specimen lived in 23.4 m depth (Table 1). Furthermore, two subfossil specimens were collected at a nearby beach, and three additional specimens came from another beach (Bakkafjörður) ca. 30 km east of Lónafjörður (Fig. 1; Table 1). All subfossil shells were extremely well preserved with the periostracum still intact. Some valves were still articulated (Table 1). This precludes extensive post-mortem transport and suggests that the shells lived in nearby shallow waters.

Both sample localities were strongly influenced by the nutrient-rich, warm Irminger Current that encircles Iceland clockwise. At times, the Polar Front shifts southward so that the Langanes Peninsula comes under the influence of the cold, nutrient-poor polar or arctic waters (Thórdardóttir, 1984; Stéfansson and Ólafsson, 1991).

It should be noted that the freshwater runoff from land has only a negligible effect on the habitat in which the bivalves lived. According to Logemann et al. (2013), the area around Langanes receives much smaller amounts of freshwater than settings around the southern coasts of Iceland. However, even at these settings, the freshwater influx is barely recorded by the oxygen isotope signature of the water. Monthly water samples from the coast near Reykjavík, for example, exhibit very little seasonal $\delta^{18}O_{water}$ changes (unpublished data by one of us, BRS).

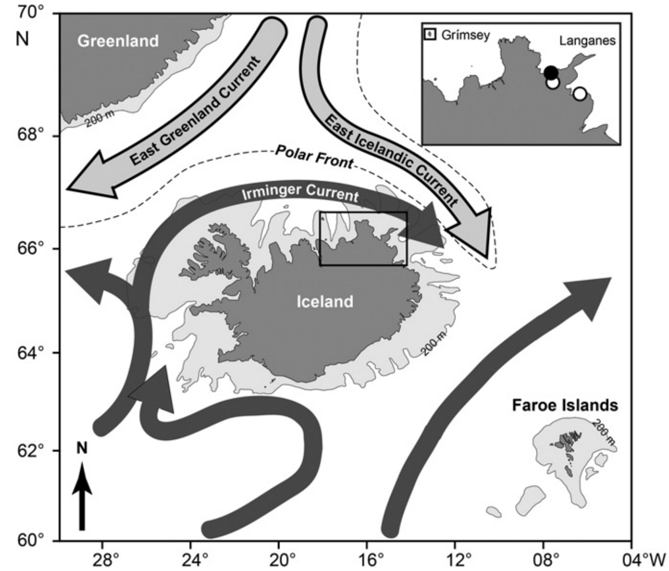

Fig. 1. Map showing oceanographic patterns in the boreal North Atlantic (based on Valdimarsson and Malmberg, 1999) and the sample localities of *Arctica islandica* shells in Northeast Iceland (filled circle: live-collected specimens at Lónafjörður, between 66°09′58.9″N, 15°22′58.9″W and 66°13′5.3″N, 15°21′54.8″W; open circles: subfossil shells from beaches near Lónafjörður, 66°09′49.8″N, 15°21′30.3″W, and Bakkafjörður, 66°00′32.4″N, 14°50′46.5″W). Also shown is the station near Grímsey Island (open square) where the SST data were recorded. Light gray: shelf 0–200 m water depth.

2.1. Radiocarbon dating ($^{14}C_{AMS}$)

To place the dead collected specimens in a rough temporal context and test whether they could have been alive during the same time interval as the live-collected specimens, we radiocarbon dated three of the subfossil shells (Table 1). For that purpose, the periostracum of the umbonal region was physically removed. Then, small carbonate chunks (~200 μg) were cut from the outer layer of the shells. Each sample represented several years' worth of growth. $^{14}C_{AMS}$ dating was performed at the ANU Radiocarbon Dating Laboratory (Fallon et al., 2010). Uncalibrated radiocarbon ages (Libby years) are given in Table 1. Calibrated ^{14}C ages and two sigma ranges were calculated using CALIB 6.1.0 (http://calib.qub.ac.uk/calib/) assuming a ΔR value (marine reservoir effect) of 58 ± 14 years (Reimer et al., 2009; Table 1).

2.2. Shell preparation and sclerochronological studies

Soft tissues were removed from the live-collected shells immediately after collection. All specimens were carefully cleaned with water to remove adherent sediment. Then, one valve of each specimen was mounted on a Plexiglass cube with EpoFix. To avoid shell fracturing during the cutting process, a quick-drying metal epoxy resin (WIKO Flüssigmetall) was applied to the shells along the axis of maximum growth. Along that axis, a 3-mm-thick section was cut from each specimen using a low-speed precision saw (Buehler Isomet 1000) equipped with a 0.4-mm-thick diamond-coated wafering blade. Next, shell sections were mounted on glass slides with metal epoxy resin, ground (800 and 1200 grit SiC powder) and polished (1 μm Al_2O_3 powder) and subsequently immersed for ca. 20–40 min under constant stirring in Mutvei's solution (Schöne et al., 2005c). This treatment greatly facilitated the recognition of annual growth patterns (Fig. 2A + B). Stained shell cross-sections were digitized with a Canon EOS 550D digital camera attached to a Wild Heerbrugg M8 stereomicroscope equipped with sectoral dark field illumination (Schott VisiLED MC 1000). Furthermore, shell portions with very narrow growth patterns were digitized with a Canon EOS 600D digital camera mounted to a fluorescence light microscope (Zeiss AxioImager.A1m stereomicroscope, HBO 100 mercury

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