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Implications of ocean acidification in the Pacific Arctic: Experimental responses of three Arctic bivalves to decreased pH and food availability



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ABSTRACT

Recent sea ice retreat and seawater warming in the Pacific Arctic are physical changes that are impacting arctic biological communities. Recently, ocean acidification from increases in anthropogenic CO₂ has been identified as an additional stressor, particularly to calcifying organisms like bivalves. These bivalves are common prey items for benthivorous predators such as Pacific walrus (*Odobenus rosmarus divergens*), bearded seals (*Erignathus barbatus*), and diving seaducks, such as Spectacled Eiders (*Somateria fischeri*). We investigated the effects of decreased pH and food availability on growth (% change in length and wet weight and allometric growth characterizations) and oxygen consumption (mg/L/hour) of three common Arctic bivalves, *Macoma calcaria*, *Astarte montagui*, and *Astarte borealis*. Two sets of experiments were run for seven and eleven weeks, exposing the bivalves to control (8.05 ± 0.02 and 8.19 ± 0.003, respectively) and acidified (7.76 ± 0.01 and 7.86 ± 0.01, respectively) pH treatments. Length, weight, and oxygen consumption were not significantly different among the varying treatments after the seven-week exposure and only one significant effect of decreased pH and one significant effect of decreased food availability were observed after the end of the eleven-week exposure. Specifically, shells of *A. borealis* displayed a decrease in length in response to decreased pH and *M. calcaria* showed a decrease in length in response to limited food. The negative effects of pH observed in the experiments on growth and oxygen consumption were small, suggesting that at least two of these species are generally resilient to decreasing pH.

1. Introduction

Atmospheric CO₂ continues to increase due to human activities such as the burning of fossil fuels and deforestation (Pelejero et al., 2005; IPCC, 2014; Meinshausen et al., 2017). The oceans act as a sink for this anthropogenic CO₂, absorbing about 30% of the anthropogenic contributions (Sabine and Feely, 2007). Increases of dissolved CO₂ into the oceans are changing the balance of chemical equilibria for the inorganic carbon system, affecting carbonate chemistry and speciation of carbon in the oceans, and resulting in ocean acidification (Caldeira and Wickett, 2003, 2005; Feely et al., 2004; Orr et al., 2005).

High latitudes will be subjected to the effects of decreased pH and ocean acidification earlier because of pre-existing natural conditions that magnify ocean acidification, including cold water temperatures (increasing dissolved gas capacities) and low concentrations of carbonate ions (Orr et al., 2005; Bates and Mathis, 2009; Fabry et al., 2009; Steinacher et al., 2009). The biological pump associated with high seasonal production and respiration also results in seasonal CO₂ accumulation that increase the vulnerability of organisms to ocean

acidification (Bates et al., 2009; Mathis et al., 2011a, 2011b; Cross et al., 2012). The proportionally high contribution of freshwater at high latitudes, including from both sea ice melt and runoff (Steinacher et al., 2009; Mathis et al., 2011a; Bates et al., 2014), is an additional factor increasing vulnerability to anthropogenic inputs of carbon dioxide. These mechanisms of natural vulnerability, in combination with anthropogenic CO₂, facilitates the persistent undersaturations (defined as $\Omega < 1$, where $\Omega = [\text{Ca}^{2+}] \times [\text{CO}_3^{2-}] / [\text{CaCO}_3]$), which are observed during the summer and fall in both the surface and bottom waters of the Bering and Chukchi Seas (Bates and Mathis, 2009; Bates et al., 2009; Mathis et al., 2011a, 2011b; Cross et al., 2013; Yamamoto-Kawai et al., 2016). In the Chukchi Sea, the shallow shelf system allows anthropogenic CO₂ inputs to immediately infiltrate bottom waters (Yamamoto-Kawai et al., 2016) and high benthic carbon metabolism allows for a seasonal efflux of CO₂ to bottom waters over the continental shelf (Mathis et al., 2014). In 2010, some bottom waters of the Chukchi Sea had pH values as low as 7.75, with bottom water aragonite undersaturations lowest in September and October (Mathis and Questel, 2013).

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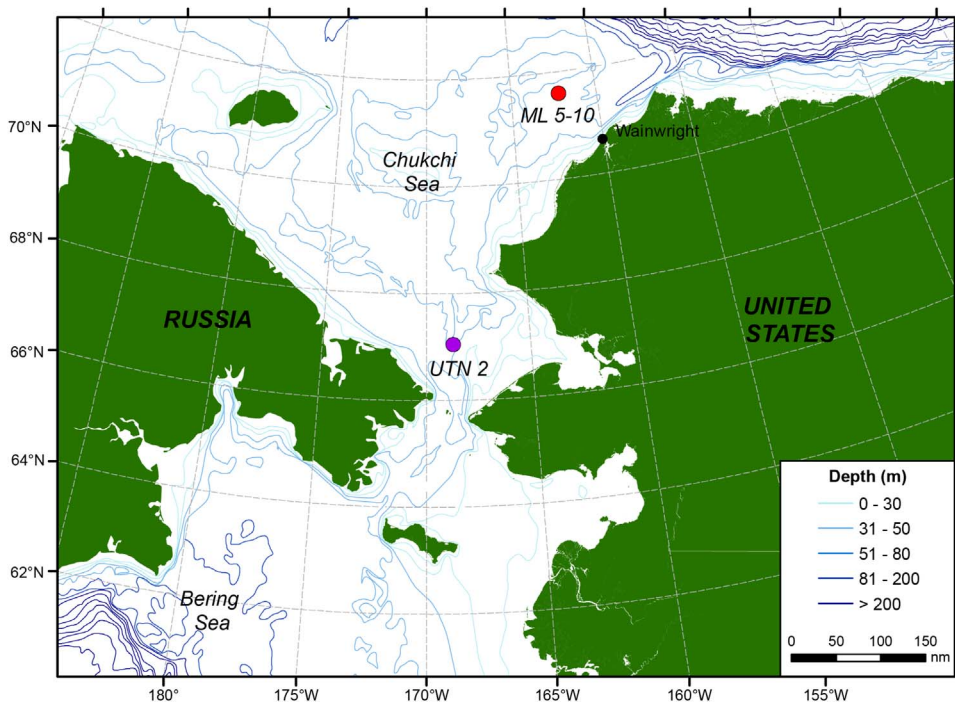


Fig. 1. Station map of Arctic Marine Biodiversity Observing Network (AMBON) cruise in 2015. Bivalves used in experiments were collected from station ML 5–10 (highlighted in red). *Macoma calcaria* collected in 2014 and 2015 for allometric comparison were collected from station UTN2 (highlighted in purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Strong impacts on organisms due to changing ocean chemistry have been widely demonstrated (e.g. Kleypas et al., 1999; Riebesell et al., 2000). Decreases in pH and the subsequent decrease in Ω values of aragonite or calcite can affect organisms in two primary ways: changes to calcification rates and disturbances to acid-base (metabolic) physiology (Fabry et al., 2008; Feely et al., 2009; Waldbusser et al., 2014). Additional changes to physiology, development, morphology (phenotypic plasticity), and behavior may also occur (Melatunan et al., 2013). Because shells and hard structures provide many benefits for the organisms that produce them, including protection from predators, dissolution of shell structure from carbonate undersaturations may lead to reduced fitness (Fabry et al., 2008).

Although the changing carbonate system in the Chukchi Sea is relatively well documented, it remains comparatively unknown how these changes will affect organisms. The high benthic biomass in the Chukchi Sea, supported by large exports of pelagic organic carbon (Dunton et al., 2005; Grebmeier et al., 2006), includes prey items that support higher trophic level organisms such as spectacled eiders (*Somateria fischeri*), gray whales (*Eschrichtius robustus*), bearded seals (*Erignathus barbatus*) and Pacific walrus (*Odobenus rosmarus divergens*) (Grebmeier et al., 2006; Moore et al., 2014). Some of these prey items include bivalves that produce aragonitic shells, although no direct studies of acidification impacts have been accomplished on the dominant bivalves in the Chukchi Sea. Elsewhere, other species of bivalves such as *Mytilus edulis* and *Crassostrea gigas* collected from estuaries in the Netherlands, have exhibited reductions in growth, decreased calcification rates, and reductions in metabolic activity in response to decreased pH (e.g. Gazeau et al., 2007). In another study, Wood et al. (2008) found an increase in calcification and metabolic activity, but at a cost to the muscle mass of the arms of the brittle star *Amphiura filiformis*. These existing studies suggest effects of decreased pH on bivalve physiology and ecology will be species-specific (e.g. Dupont et al., 2008; Fabry et al., 2008).

The goal of this study was to test the effects of decreased pH and decreased food availability on the growth (percent change and allometric growth equations), metabolic activity (oxygen consumption), and potential tradeoffs associated with metabolic activity (allometric growth classifications) of three common Pacific Arctic bivalve species. The three bivalves used were *Macoma calcaria* (Gmelin, 1791),

dominant in the southern Chukchi Sea, and *Astarte borealis* (Schumacher, 1817) and *Astarte montagui* (Dillwyn, 1817), both dominant on the continental shelves of the northern Chukchi Sea. We expect decreased pH and limited food to slow growth rates as the species allocates more energy to counteract the additional stressors. Additionally, we would expect oxygen consumption to increase in the stressed environment, as was observed by Wood et al. (2008). In a food limited situation we also expect limited growth. Finally, based on the meta-analysis of Ramajo et al. (2016), we expect that if sufficient food is available, the energy generated will be used to counteract the effects of the depressed pH, but in a multiple stressor scenario (limited food and acidified conditions) the effects will exceed the additive effects of each individual effect.

2. Material and methods

We performed two sets of experiments, one undertaken for seven weeks in the fall of 2015 and one undertaken for eleven weeks in spring of 2016, to test for impacts associated with decreasing pH and variable food supply.

2.1. Sample collection and pre-experimental holding conditions

Bivalves used in this study were collected using a 3.05 m plumb-staff beam trawl (PSBT) with 7 mm mesh and an Abookire modification (PSBT-A) (Abookire and Rose, 2005), in August 2015 from aboard the RV *Norseman II*. A total of 408 bivalves, including *M. calcaria* ($n = 87$), *A. borealis* ($n = 116$), and *A. montagui* ($n = 205$), were collected at station ML5-10 (71.6028 N, 162.2022 W, Fig. 1).

Bivalves collected at sea were maintained in groups of 15 individuals in 950 mL high density polyethylene containers at approximately 3 °C for the remainder of the cruise. Daily maintenance for the bivalves included alternating water changes, in which half the volume of water (approximately 500 mL) was removed every other day and replaced with fresh bottom water (~ 32.5 psu) collected from the CTD rosette as needed, together with gentle rotation of the container for approximately ten seconds to introduce more oxygen. At the end of the cruise, the containers were sealed with electrical tape, packed in insulated containers with ice packs, and transported from Wainwright,

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