Progress in Oceanography xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Ocean acidification risk assessment for Alaska's fishery sector

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ARTICLE INFO

Article history:
Available online xxxx

ABSTRACT

The highly productive fisheries of Alaska are located in seas projected to experience strong global change, including rapid transitions in temperature and ocean acidification-driven changes in pH and other chemical parameters. Many of the marine organisms that are most intensely affected by ocean acidification (OA) contribute substantially to the state's commercial fisheries and traditional subsistence way of life. Prior studies of OA's potential impacts on human communities have focused only on possible direct economic losses from specific scenarios of human dependence on commercial harvests and damages to marine species. However, other economic and social impacts, such as changes in food security or livelihoods, are also likely to result from climate change. This study evaluates patterns of dependence on marine resources within Alaska that could be negatively impacted by OA and current community characteristics to assess the potential risk to the fishery sector from OA. Here, we used a risk assessment framework based on one developed by the Intergovernmental Panel on Climate Change to analyze earth-system global ocean model hindcasts and projections of ocean chemistry, fisheries harvest data, and demographic information. The fisheries examined were: shellfish, salmon and other finfish. The final index incorporates all of these data to compare overall risk among Alaska's federally designated census areas. The analysis showed that regions in southeast and southwest Alaska that are highly reliant on fishery harvests and have relatively lower incomes and employment alternatives likely face the highest risk from OA. Although this study is an intermediate step toward our full understanding, the results presented here show that OA merits consideration in policy planning, as it may represent another challenge to Alaskan communities, some of which are already under acute socio-economic strains.

Introduction

Marine environments around the world are now subject to unprecedented pressures resulting from human development, including increases in temperatures and atmospheric carbon dioxide (CO_2) concentrations, changes in terrestrial runoff, and intense exploitation of resources (Doney, 2010; Halpern et al., 2008). In Alaska (Fig. 1), highly productive commercial and subsistence fisheries are located in regions projected to experience rapid transitions in temperature, pH, and other chemical parameters, crossing distinct geochemical thresholds beginning this decade (Fabry et al., 2009; Steinacher et al., 2009; Mathis et al., in press; Cross et al., 2013). Ocean acidification (OA), the term used to describe the progressive decrease in marine pH and carbonate ion concentration driven by the uptake of anthropogenic CO_2, is a global phenomenon with localized effects on marine species. These effects are predominantly negative, although there is some variability within species groups (Barton et al., 2012; Kroeker et al., 2013a; Whittmann and Pörtner, 2013). Many of the marine

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http://dx.doi.org/10.1016/j.pocean.2014.07.001
0079-6611/Published by Elsevier Ltd.

Please cite this article in press as: Mathis, J.T., et al. Ocean acidification risk assessment for Alaska's fishery sector. Prog. Oceanogr. (2015), http://dx.doi.org/10.1016/j.pocean.2014.07.001

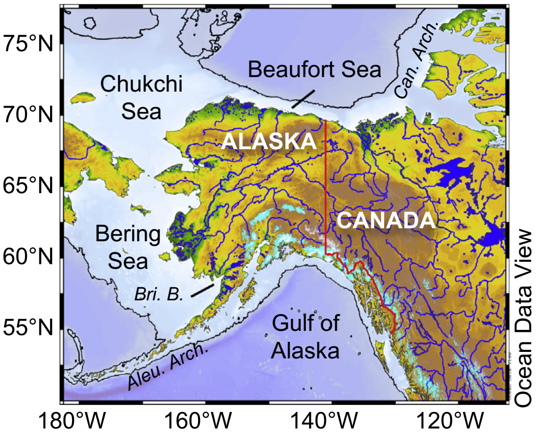

Fig. 1. Map showing the location of the major continental shelf seas around Alaska.

groups that are most intensely affected, such as mollusks and other shellfish, contribute substantially to Alaska's highly productive commercial fisheries and traditional subsistence way of life. Unfortunately, end-to-end assessments of how changes in seawater chemistry could affect key resources for specific human communities are limited in both scope and geographic coverage (Brander et al., 2012; Cooley et al., 2009; Cooley and Doney, 2009; Narita et al., 2012), and there has been no specific focus on Alaska or any other high-latitude region to date. To address this critical knowledge gap, we synthesized natural and social science data to assess the risk OA poses to Alaska's fishery sector.

Living marine resources are a critical part of Alaska's natural wealth portfolio that support a range of industries and activities, including commercial and subsistence fishing, tourism, and natural resource extraction. The revenue and protein from these sources provide economic and nutritional benefits reaching far outside the state's boundaries, to the U.S. Pacific Northwest and beyond. The state's 33,000 km coastline is 50% greater than the rest of the U.S. shoreline combined and produces about half the total commercial fish catch in all U.S. waters. The commercial fish catch also helps maintain the U.S. balance of trade on the global market. Alaska's commercial harvests had an estimated wholesale value of \$4.6 billion and supported almost 90,000 full-time-equivalent jobs in the state in 2009 (Northern Economics, Inc., 2011). At the same time, the sport and personal fishing industry supported another 16,000 in-state jobs, and \$1.4 billion of angler spending (Southwick Associates, Inc. et al., 2008). Fishing-related tourism yields over \$300 million a year in revenue for Alaska, and makes up approximately half of the state's total economic income from tourism (Southwick Associates Inc. et al., 2008). Moreover, approximately 17% of the Alaskan population, roughly 120,000 people, depend on subsistence fishing for food, with 95% of households participating in subsistence activities using fish, and 83% harvesting fish. These activities are central to many cultural customs, and additionally important sources of employment and nutrition (Fall, 2012), with two-thirds of the entire state population living along the coast (U.S. Census Bureau, 2011). For example, the Bering Sea directly or indirectly provides over 25 million pounds of subsistence food for Alaska residents, primarily Alaska Natives in small coastal communities.

Ocean acidification near Alaska

Since the pre-industrial era, human activities have increased the atmospheric CO_2 concentration by about 40% to values now at 400 ppm, which is higher than at any point during the last 800,000 years (Lüthi et al., 2008). Meanwhile, the ocean has absorbed more than 25% of the total emitted anthropogenic CO_2 (Feely et al., 2013; Sabine and Feely, 2007; Sabine and Tanhua, 2010), helping to offset some of the atmospheric consequences of humanity's waste emissions. The oceanic uptake of CO_2 triggers a series of well-understood reactions in the surface ocean that has profoundly changed seawater chemistry around the world (e.g. Doney et al., 2009; Fabry et al., 2008; Feely et al., 2004, 2008, 2009; Orr et al., 2005). This mechanism of change has already reduced the global surface ocean pH by about 0.1 units (e.g. Byrne et al., 2010; Feely et al., 2004), making the ocean 30% more acidic than in pre-industrial times. Carbonate ions (CO_3^{2-}) naturally found in seawater partially neutralize this reaction and slow the decline in pH. However, this buffering mechanism depletes the seawater of CO_3^{2-}, which makes it more difficult for organisms like mollusks and corals to create and maintain their hard shells and skeletons. The progression of OA is often discussed in terms of the "saturation state" (Ω) of calcium carbonate minerals ($CaCO_3$), which is a measure of the thermodynamic potential of a mineral to form or dissolve. When the Ω for aragonite (Ω_{arag}) and calcite (Ω_{cal}) are below 1.0, the water is corrosive to $CaCO_3$ minerals. A comprehensive review of OA chemistry can be found in Gattuso and Hansson (2011).

High-latitude oceans, like those around Alaska (Fig. 1), have naturally low CO_3^{2-} concentrations and are thus considered to be more vulnerable to the impacts of OA on shorter timescales (Fabry et al., 2009), because additional losses of CO_3^{2-} from OA represents a much greater proportional change to the system. Waters circulating along the coastline of Alaska are derived from CO_2-rich waters that are upwelled in the North Pacific, where anthropogenically induced pH changes have already been directly observed (Byrne et al., 2010). As these waters flow generally northward into the Bering Sea, with some eventually entering the Arctic Ocean, low sea surface temperature and increased solubility of CO_2 promotes naturally low CO_3^{2-} surface concentrations (Key et al., 2004; Orr, 2011; Orr et al., 2005). Uptake of anthropogenic CO_2 further reduces the surface CO_3^{2-} concentrations, pushing the high-latitude waters closer to the threshold of undersaturation with respect to aragonite (Mathis et al., 2011a). Waters around Alaska are also subject to regional physical and biological processes that exacerbate the progression of OA by additionally decreasing pH and CO_3^{2-}, or increasing the partial pressure of CO_2 (pCO_2).

In the western Arctic Ocean, which encompasses the Chukchi and Beaufort Seas (Fig. 1), potentially corrosive waters (Ω_{arag} as low as 0.5 and Ω_{cal} as low as 0.9) are found in the subsurface layer of the central Canada basin (e.g. Jutterström and Anderson, 2010; Yamamoto-Kawai et al., 2009), on the Chukchi Sea shelf (Bates et al., 2009; Mathis and Questel, 2013), and in outflow waters on the Canadian Arctic Archipelago shelf (Azetsu-Scott et al., 2010). In the Chukchi Sea, waters corrosive to $CaCO_3$ occur seasonally in the bottom waters due to the combination of natural respiration processes and the intrusion of anthropogenic CO_2 (Bates et al., 2009; Mathis and Questel, 2013). Seasonally high rates of summertime phytoplankton primary production there drive a downward export of organic carbon that is remineralized back to CO_2, which in turn increases the pCO_2 and lowers the pH of subsurface waters. The seasonal biological influence on the pH of subsurface waters amplifies existing impacts of OA (Bates et al., 2013; Mathis and Questel, 2013). Aragonite undersaturation has been observed in bottom waters of the Chukchi Sea in July, August, September, and October (Bates et al., 2009, 2013; Mathis and Questel, 2013).

Unlike the Chukchi Sea, the Beaufort Sea shelf (Fig. 1) is relatively narrow with a limited physical supply of nutrients (e.g. Carmack and Wassmann, 2006). Rates of phytoplankton primary production over the shelf have been estimated at $\sim$6–12 $g\,C\,m^{-2}\,yr^{-1}$ (Anderson and Kaltin, 2001; Macdonald et al., 2010), compared to $\geqslant$300 $g\,C\,m^2\,yr^{-1}$ (i.e. Macdonald et al., 2010; Mathis et al., 2009) in the Chukchi Sea. Although respiration of this small

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