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Ocean acidification risk assessment for Alaska's fishery sector

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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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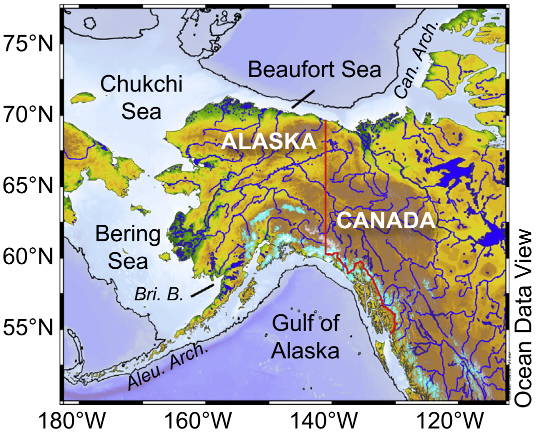


Fig. 1. Map showing the location of the major continental shelf seas around Alaska.

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 ~6–12 $\text{g C m}^{-2}\,\text{yr}^{-1}$ (Anderson and Kaltin, 2001; Macdonald et al., 2010), compared to $\geqslant 300\ \text{g C m}^{2}\,\text{yr}^{-1}$ (i.e. Macdonald et al., 2010; Mathis et al., 2009) in the Chukchi Sea. Although respiration of this small amount of organic matter at depth is not likely to lower subsurface pH markedly, OA in the Beaufort Sea may nevertheless worsen due to loss of Arctic sea ice, as the ice dampens the transfer of wind energy and limits upwelling. During an observed upwelling event in the Beaufort Sea, upper halocline water, replete in CO_2 and undersaturated in aragonite, reached the surface and moved all the way inshore along the Beaufort shelf, covering thousands of square kilometers (Mathis et al., 2012). Although some level of storm-driven upwelling is typical in this region, especially in autumn, land-fast as well as pack ice has historically returned before major late-autumn storm systems begin to pass through the region. In recent years, the western Arctic has seen an unprecedented loss of both sea ice extent and volume, so the shelves are staying sea ice-free longer each year through September and October while storm frequency and intensity reach their annual peak. In the future, the Beaufort shelf is likely to be persistently, if not continually, exposed to waters that are undersaturated in aragonite as sea ice cover continues to diminish under warming conditions (Mathis et al., 2012).

Much like the Chukchi Sea, the Bering Sea (Fig. 1) experiences seasonal variability in primary production and remineralization of organic matter (Cross et al., 2012; Mathis et al., 2011b), which both control the carbonate chemistry of the water column (Cross et al., 2013). Biological production decreases the $p\mathrm{CO}_2$ at the surface (Bates et al., 2011; Cross et al., in press) and increases Ω in summer (Mathis et al., 2011b). The $p\mathrm{CO}_2$ can range from 150 to 400 µatm in the surface mixed layer, while Ω_{arag} oscillates between an annual maximum of 3.5 and a minimum of 1.2. The only surface locations where aragonite has been observed to be undersaturated were where sea ice melt or river runoff predominated, both of which are low in total alkalinity (TA) relative to marine waters (Mathis et al., 2011b). Export and remineralization of large quantities of organic matter from surface blooms sharply increases the $p\mathrm{CO}_2$, lowers pH, and decreases Ω near the bottom, particularly in summer and autumn months. Moored sensors near the bottom showed that $p\mathrm{CO}_2$ levels exceed 500 µatm by early June and remain high well into the autumn, indicating that bottom waters are likely continuously undersaturated in aragonite for several months each year (Mathis et al., in press), primarily due to natural respiration. However, the extent, duration, and intensity of these undersaturation events will likely increase as anthropogenic CO_2 inventories continue to rise in the water column and average Ω declines. The timing and duration of these undersaturation events could be significant for the development of larval and juvenile calcifiers in the region (e.g. Long et al., 2013a,b).

Unlike the vast continental shelf regions to the north, the Gulf of Alaska (Fig. 1) does not have seasonal sea ice cover. However, it receives both low-alkalinity water (and hence lower Ω) from glacial runoff (Reisdorph and Mathis, in press; Evans et al., 2014) and upwelling of waters that are rich in CO_2 and undersaturated in aragonite from the deep Gulf of Alaska (Evans et al., 2013). Throughout most of the year, alongshore winds create a downwelling environment that keeps deeper water from penetrating onto the shelf. However, in summer these winds relax, allowing the waters that are undersaturated in aragonite to penetrate the inner shelf, causing the saturation horizon for aragonite to become as shallow as 75 m (Evans et al., 2013). Although the narrow continental shelf of the Gulf of Alaska is more than three times as deep as the Bering and Chukchi shelves, there is still a considerable remineralization of organic matter at depth that further drives a reduction in pH and Ω in the bottom waters.

Alaska's marine organisms and ocean acidification

OA appears to act more strongly on certain species and types of organisms than others (Kroeker et al., 2013a; Ries et al., 2009; Whittmann and Pörtner, 2013; Table 1). More calcifying organisms than non-calcifiers clearly exhibit significant negative responses (Kroeker et al., 2013b; Long et al., 2013a,b), and lower pH environments alter ecosystem composition toward dominance by non-calcifying organisms (Hall-Spencer et al., 2008; Wootton et al., 2008). Mollusks appear to be the calcifying group most negatively affected by OA. However, mollusks represent a very small fraction of Alaska's marine harvests, and the specific OA responses of most species harvested in Alaska, mollusks and others, have not yet been fully studied. We must therefore infer responses from studies on similar mollusk species (Table 1) and on meta-analyses of mollusks overall (e.g. Kroeker et al., 2013a), which suggest that it is more likely than not that harvested mollusk species in Alaska will experience negative effects from OA.

The biological OA responses of only two commercially important Alaskan crustacean species have been directly studied. Both red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi* and *C. opilio*) species exhibited negative responses to high-CO_2, lower-pH water (Long et al., 2013a,b). Growth of red king crab was slowed and molting success decreased in waters with a pH of 7.8, and crabs died in highly acidified conditions (pH = 7.5). A similar pattern was observed for Tanner crabs in waters with a pH of 7.5, although they had a higher survival rate. Studies on crustaceans from other locations also show negative effects on core physiological processes in response to decreased pH (Pane and Barry, 2007; Walther et al., 2010). This is particularly important in the early stages of development, when organisms tend to be more sensitive. In addition, species inhabiting cold, Arctic waters show narrower thermal tolerances in response to higher CO_2 levels (Walther et al., 2010). In several high-latitude species, negative responses to decreased pH are particularly strong when combined with other stressors such as increasing temperature (Enzor et al., 2013; Strobel et al., 2012). Moreover, deep-water species may be less tolerant to changes in pH due to the natural stability of their chemical environment (Pane and Barry, 2007).

Commercially and nutritionally important finfish appear less likely to experience direct harm from higher CO_2 levels and lower pH associated with OA, yet evidence suggests that possible food-web changes caused by OA could indirectly affect these fishes. Marine fishes with high metabolic rates and well-developed acid-base regulatory systems are believed to have sufficient capacity to respond to elevated environmental CO_2 levels (Melzner et al., 2009; Pörtner, 2008). Several studies have demonstrated that growth rates of juveniles and sub-adults of temperate and boreal marine fishes are not negatively impacted by CO_2 levels in excess of those predicted to result from OA (Foss et al., 2003, 2006). Juvenile walleye Pollock (*Gadus chalcogrammus*), an important Alaskan species, also demonstrated no significant negative effects from exposure to OA (Hurst et al., 2012). While experiments with eggs and larvae of walleye pollock did not show detrimental effects from rearing in low pH (Hurst et al., 2013), experiments on Atlantic cod (*Gadus morhua*) and Atlantic herring (*Clupea harengus*) have suggested that some commercially important boreal species can be negatively affected by OA (Franke and Clemmesen, 2011; Frommel et al., 2012). Potentially of larger concern for commercial fisheries are indirect effects: the reduction of productivity or changes in species composition of lower trophic levels that may happen as a result of OA, and the resulting effects on predatory finfish if their preferences are inflexible or prey is scarce (e.g. Kaplan et al., 2010). Successful recruitment of marine fishes is dependent upon the availability of sufficient prey resources that meet specific nutritional requirements (Litzow, 2006). Pteropods, which calcify the more soluble $CaCO_3$ mineral aragonite, are a prey for pelagic fish in subarctic and arctic regions (Orr et al., 2005). In Alaskan waters, pteropods are thought to be important prey for juvenile salmon (Aydin et al., 2005; Karpenko and Koval, 2012) and other

Table 1
Breakdown of the top 10 commercially important species, ecologically important species, and other economically important species in Alaska and the current state of knowledge regarding the physiological impact of ocean acidification on these organisms.

		Species (ranked by NMFS 2011 economic value)	Physiological impacts	References
Top 10 commercially important species	1	Walleye pollock, *Theragra chalcogramma*	Increase otolith deposition rate in juveniles	Hurst et al. (2012) and Hurst et al. (2013)
	2	Sockeye salmon, *Oncorhynchus nerka*	N.D.	
	3	Pacific halibut, *Hippoglossus stenolepis*	N.D.	
	4	Pacific cod, *Gadus macrocephalus*	No reduction in growth efficiency	Hurst et al. (unpublished data)
	5	Pink salmon, *Oncorhynchus gorbuscha*	N.D.; modeled growth decreases if pteropods decline	Aydin et al. (2005)
	6	Sablefish, *Anoplopoma fimbria*	N.D.	
	7	Snow Crab, *Chionoecetes* (any)	Uncompensated acidosis in Tanner crab	Pane and Barry (2007)
	8	King Crab, *Paralithodes*	Lower survival, growth, and calcium content	Sigler et al. (2008)
	9	Chum salmon, *Oncorhynchus keta*	N.D.	
	10	Yellowfin sole, *Limanda aspera*	N.D.	
Ecologically important species		Shrimp, *Pandalus borealis*	No negative effects on larval fertilization success or development time	Bechmann et al. (2011)
		Copepod, *Calanus glacialis*	No significant effect on egg production; pH 6.9 delayed egg hatching and reduced overall hatching success	Weydmann et al. (2012)
		Shelled pteropod, *Limacina helicina*	CaCO3 precipitation rate decrease, shell exterior dissolution	Orr et al. (2005), Fabry et al. (2008), Comeau et al. (2010 Plos One), and Bednaršek (2014)
		Cold water corals, *multiple*		Guinotte and Fabry (2008), Fish and crabs, particularly juveniles, use coral habitat as refuge and as focal sites of high prey abundance Stone et al. (2005)
Other economically important species		Dungeness crab, *Cancer magister*	Temporary acid-base shift followed by compensation	Pane and Barry (2007)
		Spider crab, *Hyas araneus*	Slower larval development and reduced larval growth and fitness	Walther et al. (2009)
		Edible crab, Cancer pagurus	High CO2 and temperature enhanced sensitivity, reduced protein synthesis rate	Metzger (2007)
		Pacific oyster, *Crassostrea gigas*	Decreased growth and survival	Gazeau et al. (2007) and Waldbusser (2001)
		Olympia oyster, *Ostreola conchaphila*	N.D.	
		Pinto abalone, *Haliotis kamtschatkana*	Decreased larval survival, increased shell abnormalities	Crim et al. (2011)
		Weathervane scallop, *Patinopecten caurinus*	N.D.	

harvested species (Moss et al., 2009). Recent studies of natural pteropod populations in the Southern Ocean in conditions similar to those currently observed in coastal Alaska have shown rapid and significant shell dissolution (Bednarŝek et al., 2012).

Risk assessments

The heavy dependence of humans on marine organisms in Alaska implies that ecosystem services based on these species could change as OA progresses (Cooley et al., 2009). Early studies of OA's potential human impacts have focused on direct macroeconomic losses likely from specific scenarios of dependence, commercial harvests, and damages to marine species (Brander et al., 2012; Cooley and Doney, 2009; Narita et al., 2012). However, indirect microeconomic impacts due to climate change are also likely to manifest, such as changes in food security or shifts in livelihoods (e.g. Allison et al., 2009; Battisti and Naylor, 2009; Cooley et al., 2012; Lobell et al., 2008). Because Alaskans involved in the fishery sector may have alternatives for employment, food sources, and recreational activities, risk assessment offers a more flexible approach for considering the complex landscape of factors affecting community risk.

In this study, we used the best available and most recent chemical, biological, and socio-economic data specific to Alaska to assess current patterns of human dependence on marine resources within the state that could be negatively impacted by OA. Using a risk and vulnerability framework based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Cardona et al., 2012), we relate multiple oceanographic variables to Alaskans' dependence on fisheries and marine ecosystem resources, while also considering demographic and nutritional characteristics of regional human communities around the state. In Section 'Materials and methods', we describe the framework, geographic regions addressed, and other data used. By synthesizing multiple datasets, we were able to make an initial assessment of current conditions throughout the state. From this we developed an overall index assessing the risk from OA for Alaska that incorporates all of these data. In Section 'Results', we present the results of this analysis as they relate to hazard, exposure, and social vulnerability, and their integration. In Section 'Discussion', we discuss the results in context with other studies, and in Section 'Conclusions', we present some brief conclusions and possible links between this work and local policies.

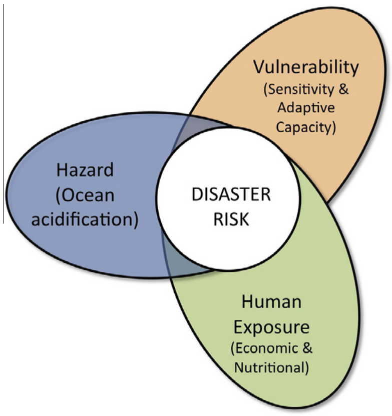
Materials and methods

Components of ocean acidification risk index

We have structured the assessment using the risk and vulnerability framework developed by the IPCC SREX (Cardona et al., 2012) for climate change, so that our findings can be evaluated in a common structure and language with other social–ecological risks from climate change. In this framework, we consider the overall "disaster risk" related to OA. Disaster risk is shorthand for the likelihood that extreme physical events will intersect with vulnerable social groups, resulting in negative effects that will require emergency intervention (Field et al., 2012). Although OA may not represent the same class of climate disaster as, for example, severe flooding, it could disrupt human livelihoods and nutrition over annual to decadal timescales, as it already has in the Pacific Northwest of the U.S. (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). In that way, OA is more analogous to climate change's effects on agriculture, which could be both long- and short-term and act through direct organism and indirect ecosystem routes. The evaluation of the disaster risk related to OA using this framework provides broad-based insights into possible ways to offset its risk, because this approach weighs natural hazards equally against socio-economic resources and liabilities.

The framing of risk and vulnerability we applied here differs slightly from the few studies that previously evaluated risk of losses from OA (i.e. Cooley and Doney, 2009; Brander et al., 2012; Narita et al., 2012). Using Cardona et al.'s (2012) definition, we assessed risk using three main components: hazard, exposure, and vulnerability. Vulnerability is made up of two dimensions, referred to as sensitivity and capacity. Within this framing, the component of exposure is independent of vulnerability. This is a slight deviation in terminology from definitions described in previous IPCC reports (2007 and 2001), which evaluated exposure as one dimension of vulnerability. Lavell et al. (2012) provide a thorough discussion of the IPCC's change in definition and its stronger focus on risk. In brief, by separating exposure out of vulnerability, they maintain that vulnerability is a latent trait of a system (social, ecological, or other), and thus can be described as independent of the hazard. Here, vulnerability is constructed based on social systems' *sensitivity* and *adaptive capacity*, concepts that are described in Section 'Vulnerability' below.[3]

The total disaster risk is based on the intersection of the hazard, the assets exposed to the hazard, and a system's vulnerability to the hazard (Fig. 2). Here, OA is the environmental hazard (navy blue region in Fig. 2) and how it is projected to change over time. Exposure refers to where organisms that could be harmed by OA are located. For this exposure component of the analysis, we focus only on living marine resources that are directly important to human communities in Alaska. Our analysis of vulnerability of the social system depends on two components: (1) Sensitivity, here defined as human communities' degree of dependence on OA-susceptible resources, which is offset by the presence of alternative resources; and (2) adaptive capacity, here encompassing the human communities' estimated ability to respond with proactive adaptation in anticipation of an environmental challenge. Here, we assessed the overall risk from OA as a function of all of these contributing factors.



Consistent with IPCC SREX (2012)

Fig. 2. Schematic of risk framework used in this study, adapted from IPCC SREX. Disaster risk is a function of the intersection of a hazard (here, OA), exposure of human communities to the hazard/disaster, and vulnerability of the human system to changes caused by these factors.

Geographic analysis units

The fisheries and socio-economic datasets used here were originally divided into specific geographic regions that were not all aligned. For example, fishing management areas are unique at the species level while fishery harvest data relates to landing ports and land-based census areas. To compensate for these geographic differences between datasets, we chose to spatially fit each distinct dataset into the standard federally assigned census areas and boroughs for the state of Alaska (Alaska Department of Labor and Workforce Development, 2011).

The marine coastal zones around Alaska can be broken down into four broad regions and extend roughly from the shoreline to the outer continental shelf, which is where nearly all commercial and subsistence harvest is conducted. These regions are the Gulf of Alaska (GOA), the East Bering Sea/Aleutian Islands (EBA), the Chukchi Sea (CS), and the Beaufort Sea (BS). Each region is impacted by unique biogeochemical processes, and we have broken them down here based on a number of factors including general ocean circulation patterns, rates of production, distribution of fisheries, and sea ice extent. The geographic extent of each region varies considerably, with the EBA and CS covering large regions due to their broad continental shelves, while the GOA and BS cover much smaller areas.

Hazard

We quantified the hazard of OA using surface pH and the saturation state of the two $CaCO_3$ minerals aragonite (Ω_{arag}) and calcite (Ω_{cal}). To illustrate the past, present, and projected chemical properties in Alaskan waters, we use output from the coupled climate-ocean model NCAR CESM1-BGC (National Center for Atmospheric Research Community Earth System Model with a biogeochemistry model enabled; Lindsay et al., 2014; Long et al., 2013a). The CESM1-BGC model is a descendant of the NCAR CCSM4 model, differing only in the inclusion of an ocean biogeochemical model (Moore et al., 2004) and three-dimensional atmospheric CO_2 tracers, which are each interactively coupled to each other and to the

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[3] There are many ways that scholars and practitioners employ the terms vulnerability and risk (differences discussed in, but not limited to, Cardona (2004), Cardona et al. (2012), Cutter et al. (2008), and Füssel (2007)). We sought to avoid adding to the confusion of the literature. For this reason, we remain consistent with conceptual framing of the most recent IPCC reports because these represent a consensus on the complicated topic among a large number of international experts that specialize in the concepts' theoretical derivations.

land biogeochemistry model (Lindsay et al., 2014). These improvements allow additional biogeochemical feedbacks to the physical climate (Lindsay et al., 2014). Historical atmospheric CO_2 emissions were used to force the simulation over the industrial period (Lindsay et al., 2014), while the future simulation followed the atmospheric CO_2 emissions from the IPCC RCP 8.5 (van Vuuren et al., 2011) scenario. CESM-modeled seawater CO_2 levels are therefore influenced primarily by atmospheric CO_2 levels, ocean physics, and respiration and primary production in the ocean. The simulated changes in surface pH, Ω_{arag} and Ω_{cal} from the past (1880–1889) to near-present (2003–2012) and end of this century (2090–2099) are calculated as decadal mean values for each region (see Section 'Geographic analysis units') and time period.

For the hazard component of the risk framework, we ranked the four ocean regions according to the forecasted level of decrease in decadal mean Ω_{arag} between the near-present (2003–2012) and the end of this century (2090–2099). We anticipate that ocean regions with greater projected decreases in mean surface Ω_{arag} will be at greater risk of the hazard represented by OA. Each of the marine geographic regions abutted multiple census areas on land, so multiple census areas experienced the same hazard. Inland census areas were assigned the mean change in surface Ω_{arag} for the four ocean regions. Relative hazard was scored by ranking the ocean regions from 1 (smallest projected $\Delta\Omega_{arag}$) to 4 (greatest projected $\Delta\Omega_{arag}$).

Exposure

Exposure to the effects of OA is related to which marine resources are important to human communities and susceptible to OA. In a vulnerability and risk analysis, exposure typically is guided by the question of "who or what will be exposed to the given hazard or stressor?" In our application of the framework, exposure refers to where organisms are located that could be harmed by OA. However, absent of the specific locations of the organisms, we represent their distribution with two metrics that indicate the organisms' relative importance to certain areas. Metrics of importance of organisms are based on two social values: economic and nutritional. The side benefit of using social importance to represent the geographic location of organisms is that it more accurately represents the aspect of the organisms we are interested in for this risk assessment.[4] Given that OA affects some marine organisms more than others (and in different ways), we accounted for this difference using the state of the science as it applies to marine organisms in Alaska. To date, only a few of the important fishery species in Alaska have been tested for a response to OA (Hurst et al., 2012, 2013; Long et al., 2013a,b), and these physiological sensitivity evaluations do not yet provide comprehensive evaluations of the full range of potential OA impacts and their consequences to population- or ecosystem-level dynamics. But it is standard to assume that negative effects on individuals will result in some degree of negative population-scale consequence (Kroeker et al., 2013a,b). Furthermore, Alaskans' direct and measurable use of OA-susceptible species is primarily through fishing and fishery-related activities, so marine biological data used in this study are restricted to species with important commercial or subsistence harvests.

To transform our knowledge of how Alaskan species are likely to respond to OA (Table 1 and Section 'Introduction') with socioeconomic effects, we sought to quantify the value of individual species to Alaskans. However, data reporting confidentiality rules and the lack of research on individual Alaskan species required that we pool harvest data into increasingly coarse biological categories as our analysis became more geographically detailed. For statewide analyses, confidentiality-based data gaps were minor at the species level, so we presented data by species or by major functional groups as in Cooley and Doney (2009). This grouping allowed for some consideration of the differential species-specific responses exhibited by Alaskan species. For census area-scale assessments, both commercial and subsistence harvest data were pooled into three major groups: shellfish, salmon, and other finfish. The shellfish category included all species of crab, shrimp, clams, octopus, squid, scallops, urchins, and sea cucumbers; the salmon category included all species of salmon; and the "other finfish" category included everything else. This grouping strategy reflected the finding that mollusks from other regions experience net negative effects from OA (Kroeker et al., 2013a,b), and that red king crabs and Tanner crabs from the Alaska region also exhibit negative responses from OA (Long et al., 2013a,b; see also Table 1). The negative responses of these taxa are due to direct effects, such as changes on calcification, growth, survival, development, and abundance (Kroeker et al., 2013a,b).

It is also expected that Alaskan species that prey on calcifying species would experience indirect negative effects associated with food web shifts or prey abundance decreases; this possibility has been proposed for pink salmon (*Oncorhynchus gorbuscha*), which prey on pteropods, a potentially vulnerable zooplankton group (Aydin et al., 2005; Fabry et al., 2008; Bednaršek et al., 2012). Moreover, an ecosystem-based model for the California Current projected substantial declines in harvests of species that prey on calcifiers in scenarios including OA (Kaplan et al., 2010). Because of salmon's distinct life history and the importance of their harvests to Alaska, we included them as a separate biological group at risk from the indirect effects of OA. We assumed other finfish harvests were unlikely to be significantly affected by OA; this decision was based on the lack of information demonstrating direct negative responses to OA or strong trophic linkages of specific species or finfish groups to vulnerable prey such as pteropods. Mathematically, this distinction between directly affected, indirectly affected, and unaffected groups was made by weighting the shellfish group by 2, the salmon group by 1, and the other finfish group by 0 whenever metrics were calculated relating to the proportional contribution of each to overall fishery activities.

The first aspect of marine organisms we quantified represented their economic value to Alaskans. The commercial economic value of marine organisms was determined from species-specific commercial harvest quantity and price data provided by Alaska Department of Fish and Game (ADF&G; C. Tide, personal communication), which includes information about both commercial harvesting and processing. Commercial fishing harvest quantity data were reported by weight in pounds for the total annual harvest for 2011, the most recent year available. The ex-vessel value of these harvests, or the value of the harvests received by fishermen and before processing, is from the Commercial Operator's Annual Report (COAR) and available from Cathy Tide (personal communication). Harvest quantity per capita and all per capita calculations described henceforth were calculated with population data from the 2011 U.S. Census Survey. Confidentiality agreements between records of fishermen, vessels, and/or processors and the reporting agency (ADF&G) prevented disclosure of data where three or fewer companies were involved, and this created a few gaps in data obtained for species and/or census areas. The number of people involved in commercial fishing was determined primarily through licensing and permit data (ADF&G Administrative Services Division) and state employment estimates. All 2011 permit holders claiming Alaskan residency and having an Alaskan address were included in the number of people involved in commercial fishing. The number of crew associated with each of these permits was also

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[4] Other studies that focus on *ecological* risk of organisms to OA alternatively would be less interested in social values and more interested in the organism's role in ecosystem function.

included, based on ADF&G estimates using 2010 data. The number of people involved in processing includes both residents and nonresidents, but all processing activities take place within the state (Alaska Department of Labor and Workforce Development, 2011).

Marine resources supplying food to Alaskans was the second aspect of marine organisms' exposure to OA that we investigated. Alaska residents' nutritional dependence on marine resources was gauged from subsistence fishery harvest quantity data from the ADF&G (J. Fall, personal communication). These data are reported as the total salmon, total shellfish, and all "other fish" in usable pounds per person, based on aggregated household survey data, post-season survey records, and permit data taken throughout the state, grouped into federally designated census areas for this study (J. Fall, personal communication). Subsistence fishing activities considered here included all personal, noncommercial fishing activities performed in state waters.

Human exposure to OA through fishery resources were semi-quantitatively assessed using a metric (E) that sums the measures of both commercial economic and nutritional importance. For notational clarity, when describing our index we used the term "economic" and the subscript E to refer to commercial harvest and processing activity. We used the term "nutritional" and the subscript N to refer to subsistence activity.

For each census area, we quantified exposure due to economic value, E_E, as:

$$E_E = 2C_{R,Sh} + C_{R,Sl},$$

where $C_{R,Sh}$ is the percent of total commercial revenue from shellfish, and $C_{R,Sl}$ is the percent of total commercial revenue from salmon. To overcome data gaps caused by reporting confidentiality rules, we first calculated the statewide average values for harvests of each species per company (pounds) and revenues from each species per company (dollars) for the "shellfish" and "salmon" categories. Then we estimated the additional harvest weight and revenue values that had not been reported by multiplying the number of companies in each census area whose data were confidential by these statewide average values, and adding the estimated additional harvest and revenue estimates to the reported totals.

Exposure in terms of nutritional importance of marine organisms, E_N, was calculated as:

$$E_N = 2S_{WT,Sh} + S_{WT,Sl}$$

where $S_{WT,Sh}$ is the percent of total subsistence harvest weight from shellfish; and $S_{WT,Sl}$ is the percent of total subsistence harvest weight from salmon. The resulting census area values for both E_E and E_N were divided into quartiles and scored from 1 to 4, with lowest exposure values receiving a score of 1 and highest a 4. Scored nutritional and economic exposure were then evenly weighted and combined to determine exposure:

$$E = 0.5E'_E + 0.5E'_N,$$

where the prime symbols indicate the quartile-classified quantities scored from 1 to 4 as described above.

Vulnerability

The severity of impacts from OA (and other environmental hazards) depends on not only the level of exposure of the system to the hazard, but also the degree of vulnerability of the system to the hazard. Vulnerability is the degree to which a system (social, natural, or otherwise intertwined) is susceptible to harm from a given hazard (Cardona et al., 2012). We use vulnerability to describe the social system because we are interested in the risk that OA presents to humans. There is also a growing literature that focuses on organisms, in which the term vulnerability is used to describe biological or ecological susceptibility of species or ecosystems (or their services) to a given hazard (e.g. see Foden et al., 2013; Williams et al., 2008). The concept of vulnerability is defined and evaluated in several different ways across (and even within) disciplines (Füssel, 2007). Here, we follow the terminology and conceptualization of vulnerability within risk as presented in Cardona et al. (2012). This largely stems from the disaster risk management community and has been united with the climate adaptation community in the Oppenheimer et al. (2014) and Cardona et al. (2012) as the way the IPCC now uses the terms. In this conceptualization, vulnerability is assessed independent from exposure to the hazard and rather seeks to understand those population characteristics that inherently increase Alaskans' propensity to suffer from OA. To gauge this social vulnerability, we evaluate the social system's sensitivity and adaptive capacity to OA. Here, the terms of sensitivity were viewed as the degree of human reliance on OA-susceptible organisms. In terms of adaptive capacity, this encompasses characteristics of the current socio-economic system that afford flexibility in the face of changing ecosystem services, which includes the ability of human systems to prepare for, respond to, or adapt to changes from OA.

Sensitivity

Sensitivity (V_S) is measured here using both commercial harvest and subsistence harvest data. In contrast to exposure, which primarily documents the extent that OA-susceptible species are present and valued in Alaska, sensitivity as quantified also includes scaling factors related to people's varying degree of reliance on the species. This scaling allows an assessment of the relative importance of this economic or nutritional dependence to individuals and the region.

Economic sensitivity, $V_{S,E}$, is evaluated for each census area. $V_{S,E,Q}$ is the estimated amount of revenue per capita from harvesting and processing OA-susceptible species, calculated as the estimated gross earnings of harvesters (data: Alaska CFEC (Commercial Fisheries Entry Commission), 2011) plus the wages from processing, divided by the estimated harvester and processor workforce. Estimated earnings of both resident and nonresident processor workers are pooled and treated together, assuming that nonresident processors are primarily spending their earnings within the state. The processor workers' earnings used here represent an upper bound for spending/local economic contributions, as the earnings are not traceable by the worker's residence. Due to this limitation, our estimates could place processor-worker spending up to 54% higher than it really is. This estimate is based on the ratio of non-resident workers to resident workers.

$V_{S,E,C}$ is estimated by multiplying the percent of the population involved in harvest and processing (calculated from CFEC and U.S. Census data) by the percent of commercial harvests, by weight, devoted to shellfish and salmon (calculated from ADF&G-based estimates for each census area developed using the data gap-closing procedure described in Section 'Exposure'). Once both $V_{S,E,Q}$ and $V_{S,E,C}$ are calculated, they are divided into quartiles, which equate to scores as described above. The index value of $V_{S,E}$ is then calculated as:

$$V_{S,E} = 0.5V'_{S,E,Q} + 0.5V'_{S,E,C},$$

where primes indicate the quartile-classified and scored quantities. Resulting $V_{S,E}$ values for each census area are then divided into quartiles and scored.

To assess sensitivity due to nutritional dependence ($V_{S,N}$), we examined the proportion of per capita subsistence harvest weight devoted to calcifiers ($V_{S,N,C}$) and salmon, and the quantity of subsistence harvests per capita ($V_{S,N,Q}$). $V_{S,N,C}$ is calculated as:

$$V_{S,N,C} = 2S_{Sh,WP} + S_{Sl,WP},$$

where $S_{Sh,WP}$ and $S_{Sl,WP}$ are the percent of per capita subsistence harvests by weight from shellfish and salmon, respectively. Subsistence harvest weight and composition are from ADF&G (J. Fall, personal communication). $V_{S,N,Q}$ is calculated as the total quantity of subsistence harvests per capita (pounds/person). Once $V_{S,N,C}$ and $V_{S,N,Q}$ are each divided into quartiles and scored, $V_{S,N}$ is calculated as:

$$V_{S,N} = 0.5V'_{S,N,Q} + 0.5V'_{S,N,C}.$$

$V_{S,N}$ values for each census area are then divided into quartiles and scored.

Adaptive capacity

The capacity to adapt, prepare for, or respond to the impacts of OA is the other component used to estimate vulnerability.[5] To examine this adaptive capacity, we created a metric that broadly assesses the resources Alaskans have even if current community stability is altered through changes in income or nutrition (Allison et al., 2009; Cooley et al., 2012). Very little research has investigated the multiple dimensions of adaptive capacity as related directly to OA (other than Cooley et al., 2012); however, a lot of scholarly work looks at the capacity of groups of people to deal with the damage from climate change, including a focus on fisheries (e.g. Allison et al., 2009; Berkes and Jolly, 2001; Cinner et al., 2009; Cinner et al., 2012; Coulthard, 2008; Hughes et al., 2012; Jepson and Colburn, 2013; Marshall et al., 2013). We gathered indicators to represent four main areas of capacity: economic stability, educational attainment, job diversity, and food accessibility. Economic stability is measured via four variables: personal income per capita, household dependence on Permanent Fund Dividend (PFD) payments, poverty, and unemployment. (The Alaska PFD is a financial dividend paid to all Alaska residents who have lived in the state a full calendar year.)

Economic stability. Economic stability-related data were from the Alaska Department of Labor and Workforce Development (2012a,b) and U.S. Census Bureau (2011). Per capita personal income (for the past 12 months in 2010 inflation-adjusted dollars) was taken from 2006–2010 U.S. Census Bureau data (U.S. Census Bureau, 2011). This is a similar measure to GDP per capita; however, it includes earnings classified as self-employment, which make up the majority of the fishing industry's income. Household dependence on the PFD was calculated by multiplying the average household size for each census area by the 2010 PFD allotment ($1281 per capita; Alaska Department of Revenue, Permanent Fund Dividend Division, 2011) and dividing by the median household income, from the 2006–2010 U.S. Census Bureau data (U.S. Census Bureau, 2011). Poverty is represented as the percent of people of all ages in poverty from 2006–2010 (U.S. Census Bureau, 2011). Unemployment rates are from the Alaska Department of Labor and Workforce Development (2012a). These data understate unemployment somewhat, as they do not account for unemployed people who have stopped actively searching for work (Alaska Department of Labor and Workforce Development, 2012a).

Education. Education is commonly used to represent people's ability to access and act on new information as one dimension of adaptive capacity. The indicator used for educational attainment in our study is the percent of people 25 years old and over that have completed high school or beyond, 2006–2010 (U.S. Census Bureau, 2011).

Job diversity. For people who rely on OA-susceptible organisms, though possibly unappealing, one adaptation option may be to seek alternative employment outside of fisheries. To represent the alternative employment options, we created a job diversity measure. To calculate this type of diversity, we used the total number of current industry types per census area from the U.S. Department of Labor (U.S. Department of Labor, Bureau of Statistics, 2012). This sums the number of employment divisions, or industry units, existing in each census area (i.e. transportation sector, food sector, health sector, etc.). Using these values, we are able to quantify the number of different job, or industry types that are reported within the specific census area with earnings. We assume these values are representative of job diversity. These data are reported annually and can be viewed as a quantitative measure of potentially available employment opportunities unrelated to fishing, because it counts all other trades but excludes self-employment, which is the usual classification for fishing activities.

Food accessibility. In cases where food is not abundantly available to a community, we consider this inaccessibility to reduce the community's capacity to cope with loss a food source (caused by OA). Food accessibility is estimated by the average annual food cost in a community, assuming that high food prices reflect long supply chains and inaccessible supplies, and they also make food less economically accessible to people in the community. Weekly food costs by community relative to Anchorage's food costs were determined as part of a long-term food cost survey (B. Luik, personal communication). Monthly averages for each census area were calculated from the survey data and multiplied by 12 months to yield annual food cost estimates. Survey data for March, June, September, and December were averaged for an annual value. Some communities were not surveyed in every period; in those cases, averages were taken from existing data points. The communities in the survey were matched to their respective census area (CA)/borough. Census areas that were not surveyed use data from the closest surveyed area. Anchorage prices are used for comparison, as the area is a large market, yet one whose prices behave differently from those in the contiguous U.S.

We combine these seven variables into an index of "adaptive capacity" (V_C) using the weighting and aggregating methods from Halpern et al. (2012), the Human Development Index (United Nations Development Programme, 2011), and the World Risk Report (Alliance Development Works et al., 2012). Datasets for each variable were scaled from their original values to a normalized range between 0 and 1.0. Finally, V_C is determined as a weighted sum of the scores for each of the index variables (I_1, I_2, ... , I_7) and their respective weights ($\alpha_1, \alpha_2, \ldots, \alpha_7$).

$$V = \sum_{n=1}^{7} I_n\alpha_n$$

where I_1 = size of the economy, measured by per capita personal income; I_2 = poverty; I_3 = unemployment rate; I_4 = the PFD contribution per household; I_5 = educational attainment; I_6 = industry diversity; and I_7 = food accessibility. α_1, α_5, α_6, α_7 are 100, and α_2, α_3, α_4 are 33. V_C values were divided into quartiles and scored so that the lowest values, indicating low adaptive capacity, received a score of 4 and the highest values and adaptive capacity receive a score of 1.

Risk index

We developed an overall index to combine the different metrics developed for hazard, exposure, and vulnerability, and to allow relative evaluation of risk factors for each Alaskan census area. Once each metric was itself divided into quartiles and scored so that low

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[5] We do not differentiate between coping and adaptive capacities here (see Cardona et al., 2012), but acknowledge that this may be the topic of future social science research that seeks to contribute to the OA field.

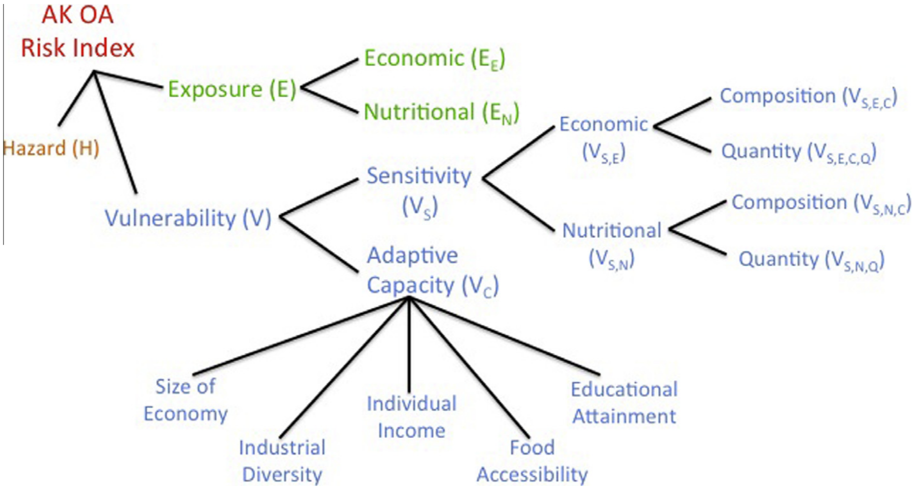

Fig. 3. Components of the risk index. Each branch is evenly weighted relative to others at the same level.

exposure, hazard, or vulnerability received low scores, etc. (indicated symbolically by primes), the final index I was calculated assuming even weighting of each component (see Fig. 3):

$$I = 0.33H' + 0.33(0.5E'_E + 0.5E'_N) + 0.33\left(0.5V'_C + 0.5\left(0.5\left(0.5V'_{S,E,C} + 0.5V'_{S,E,Q}\right) + 0.5\left(0.5V'_{S,N,C} + 0.5V'_{S,N,Q}\right)\right)\right)$$

$$I = 0.33H' + 0.33(0.5E'_E + 0.5E'_N) + 0.33\left(0.5V'_C + 0.5\left(0.5\left(0.5V'_{S,E,C} + 0.5V'_{S,E,Q}\right) + 0.5\left(0.5V'_{S,N,C} + 0.5V'_{S,N,Q}\right)\right)\right)$$

In the above equation, the first term relates to the hazard, the second to exposure, and the third to vulnerability. Last, we divided I into three levels, corresponding to lowest risk, moderate risk, and highest risk, respectively.

Results

Hazard

Model simulations (Fig. 4) indicate a rapid progression of OA in Alaskan waters, with a southward shift of habitats suitable for OA-sensitive organisms. Modeled preindustrial pH was highest in the BS region ($\text{pH}_{\text{preind}}$ 8.17, Fig. 4a); however, model results also indicate that this region experienced the largest preindustrial to present day change of pH ($\Delta_{\text{pH}} = 0.14$), which is above the global average change of surface pH (e.g. Feely et al., 2004) and consistent with recent observations in the region (e.g. Cross et al., 2013). Present-day simulations show mean surface pH values of 8.03–8.05 in all four regions (Fig. 4b), with the largest future surface pH changes projected for the BS ($\Delta_{\text{pH}} = 0.37$), where mean surface pH is forecasted to decrease to 7.66 by the end of the century (Fig. 4c). There were large regional differences in preindustrial Ω_{arag}, which was lowest in the BS (~1.4) and highest in the GOA (2.07). Since the preindustrial era, surface Ω_{arag} in the BS decreased by 0.37 units, pushing the system close to year-round aragonite undersaturation. The fastest future change in Ω_{arag} is projected for the GOA ($\Delta\Omega_{\text{arag}} = 0.79$), which will lead to a shoaling of the aragonite saturation horizon by 179 m. By 2100, all waters around Alaska are projected to be perennially undersaturated with regard to aragonite, and waters in the BS and CS are even projected to be undersaturated with regard to calcite during parts of the year. Only habitats within EBA and GOA will remain supersaturated with respect to calcite during this century, with $\Omega_{\text{cal}} = 1.31$ and $\Omega_{\text{cal}} = 1.52$, respectively. Table 2 summarizes the changes between past, present, and future.

Exposure

Because risk to the human populations in Alaska from OA operates through potential changes in populations of specific marine species, we considered exposure to only include OA-susceptible species that are also important to humans. Although Alaska's largest fisheries, both by revenue and by weight, rely on finfish such as pollock, salmon, and halibut, a substantial portion of both commercial and subsistence fisheries rely on mollusks and crustaceans. The ADF&G has published summer harvest distribution maps for some crab and clam species, which we have merged (Fig. 5), illustrating the intersection of the oceanographic hazard of OA, the presence of OA-susceptible species, and human uses of these species. Most commercially harvested crab species are primarily taken from Bristol Bay and the Bering Sea, while commercially and nutritionally important Tanner crabs are found in the GOA near the coast. In contrast, clams popular with subsistence harvesters are located very near shore, along the Aleutians and all along Alaska's southern coast bordering the GOA. In other basins, there is evidence that warming has resulted in shifts of finfish species (Cheung et al., 2013), but the effects of OA on biogeography are still not well known.

To examine exposure of OA on Alaskan harvests in more detail, we divided the list of Alaskan commercially harvested species for 2011 reported by ADF&G into major taxonomic groupings as in Cooley and Doney (2009): clams, scallops, urchins, shrimp, crabs, calcifiers' predators, top predators, those unaffected by OA, and those whose response to OA is unknown (Fig. 6). Calcifiers' predators dominate the array of species caught. However, when commercial harvest data are viewed by weight and revenue, a more complex picture emerges (Fig. 7). Although calcifiers' predators also lead the commercial harvest by quantity and revenue, the commercial importance of crabs and top predators also emerges. Table 3 provides insight into the completeness of these data; for most taxonomic categories, we have data from the majority of companies purchasing these species and the majority of species being harvested. Only data for scallops (1 species, 2 companies) and echinoderms (1 species, 1 company) remained confidential; we assume the small number of species and companies involved

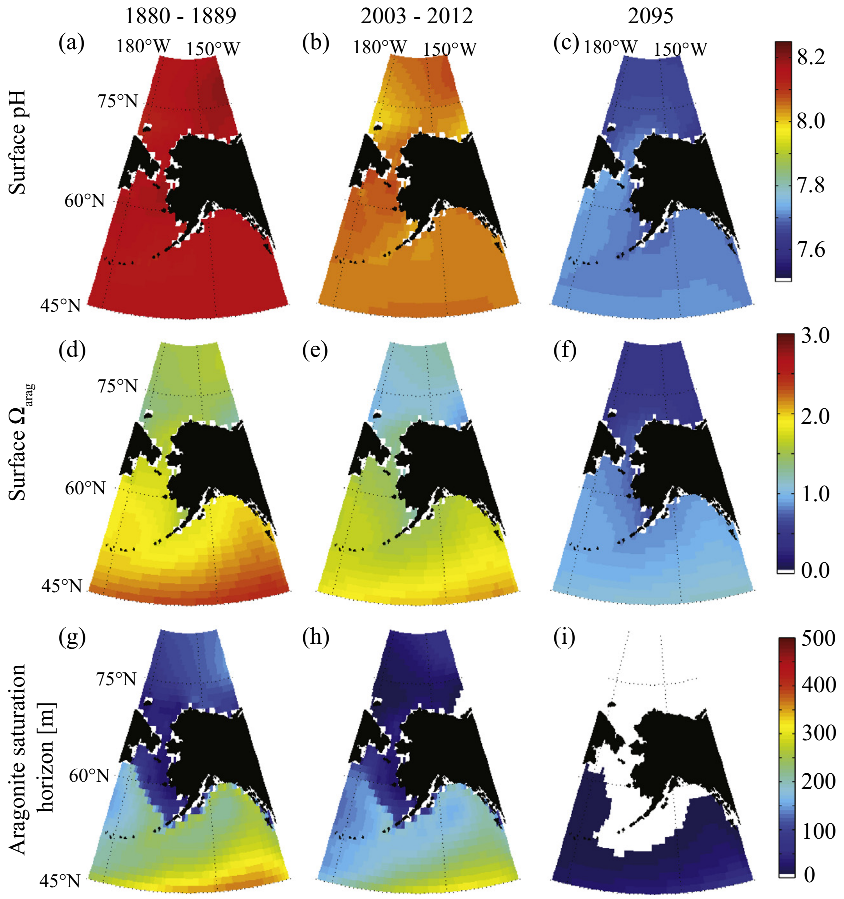

Fig. 4. Surface (top) pH, (middle) Ω_{arag}, and (bottom) saturation horizon (m) for (left) 1880–1889, (middle) 2003–2012, and (right) 2095, calculated from CESM output.

Table 2
Modeled average changes (Δ) in Ω_{arag}, Ω_{calc}, pH, temperature, and salinity from the past (1880–1889) to the present (2003–2012), and the present to the future (2095).

Parameter	Change in parameter (Δ)	Chukchi Sea	Beaufort Sea	Bering Sea	Gulf of Alaska
Ω_{arag}	Present–past	−0.30	−0.37	−0.26	−0.31
	Future–present	−0.59	−0.52	−0.68	−0.79
Ω_{calc}	Present–past	−0.48	−0.59	−0.42	−0.50
	Future–present	−0.94	−0.84	−1.09	−1.26
pH	Present–past	−0.11	−0.14	−0.10	−0.10
	Future–present	−0.35	−0.37	−0.35	−0.34
Temperature	Present–past	0.52	0.41	1.28	1.25
	Future–present	2.70	2.48	4.15	3.40
Salinity	Present–past	−0.48	−0.52	−0.12	−0.07
	Future–present	−0.94	−0.05	−0.51	−0.40

suggests that these harvests are relatively small compared to others.

Examining commercial harvest characteristics by CA shows some important regional patterns (Figs. 8 and 9). Revenues from shellfish are most important in southeast and southwest Alaska (Haines through Wrangell and Aleutians East through Lake and Peninsula, respectively). Revenues from salmon are important everywhere in the state, but especially in Alaska's interior and western CAs. When we filled gaps associated with unreported harvests or revenues using the state average per company multiplied by the number of companies not reporting, we found that we overestimated both shellfish harvest weight and revenue by 4% and underestimated salmon harvest weight and revenue by 1–2%, compared to ADF&G-reported statewide total harvest weights and revenues. We conclude that the estimates we applied to fill confidentiality-based data gaps do not materially change the results of the investigation.

Finally, exposure to OA through nutritional importance was explored using subsistence data. Salmon constitute 20–85% of subsistence diets throughout Alaska (Fig. 10) and is an especially large component of subsistence diets in the interior and western CAs. Shellfish are a large component of subsistence diets in southeast Alaska and are also important in subsistence diets in south central and southwest areas. Meanwhile, other fish contribute 20–70% to subsistence diets statewide, with a mode around 35%. Assuming proportions represent some measure of preference, salmon and shellfish are the preferred subsistence taxa, while also being likely to suffer from OA.

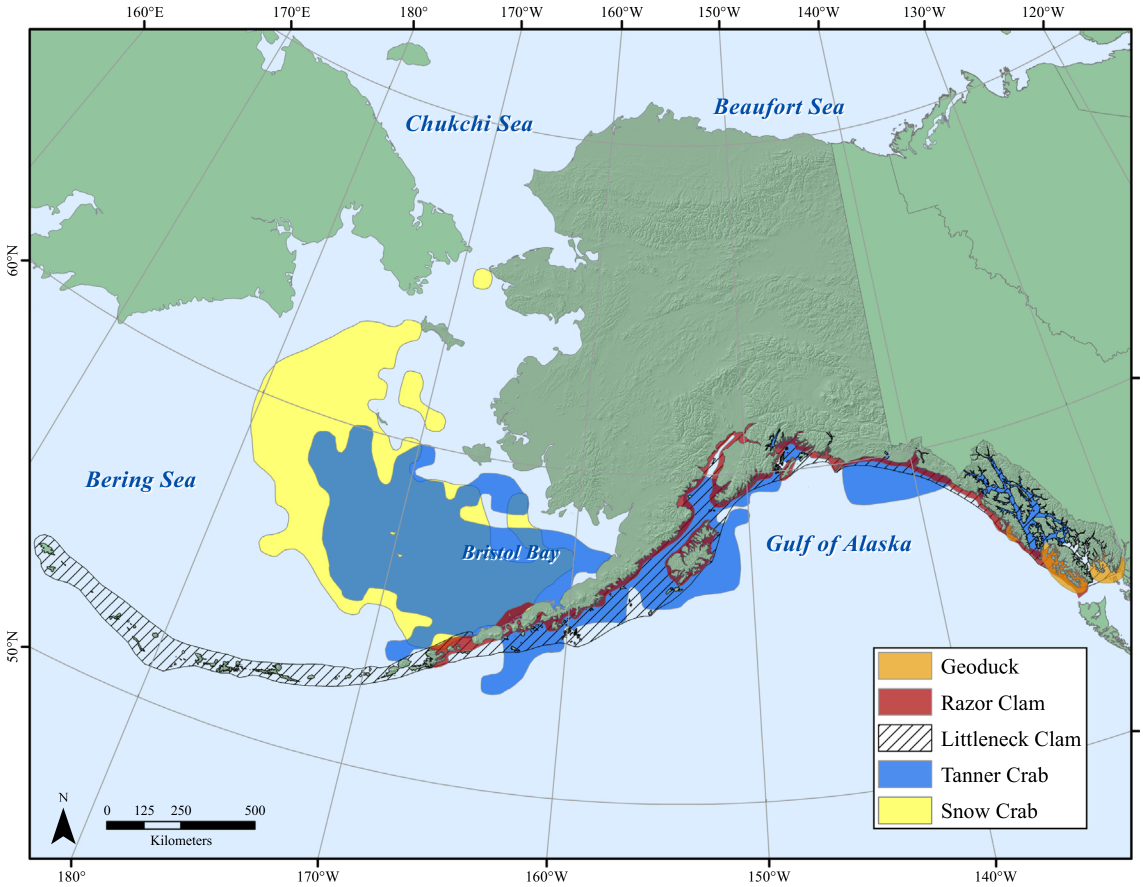

Fig. 5. Geographic range of Tanner and snow crabs, geoduck, littleneck, and razor clams (adapted from ADF&G).

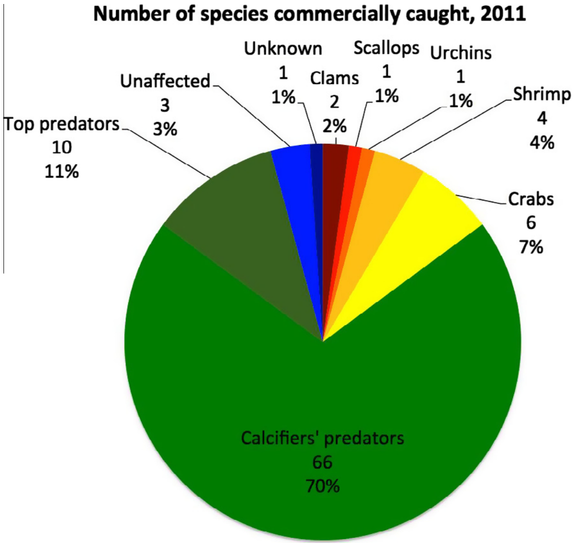

Fig. 6. The list of commercially harvested species in Alaska is dominated by finfish that prey on calcifiers during some or all of their lives or part of the seasonal cycle.

Vulnerability

Sensitivity, or the degree of economic and nutritional reliance of the human community on OA-susceptible species, makes up one half of vulnerability, as calculated in this study. Sensitivity metrics concerning nutritional dependence were based on per capita rates of nutritional dependence on OA-susceptible groups (here, shellfish and salmon). One metric was based on the proportion of OA-susceptible species consumed in a CA, and the other was based on the overall quantity of subsistence harvests per capita. Together, the two metrics provide insight into overall nutritional dependence on OA-susceptible groups. In southern and western Alaska, there were both high proportions of shellfish consumed per capita and large quantities of subsistence harvests per capita (especially southeast Alaska; Table 4). Northern and interior areas tended to have either a larger array of groups being harvested or a larger per capita consumption of subsistence harvests, but not both in the same community.

Sensitivity metrics concerning economic dependence were based on data concerning the per capita earnings of the population involved in commercial harvesting and processing and an estimate of the proportion of the population involved in harvest and processing of OA-susceptible species. Relative to other Alaskan regions, southern Alaska has the highest economic dependence on these species via commercial harvesting and processing (Table 4).

The other half of our vulnerability score is driven by the human community's adaptive capacity. In this study, the adaptive capacity metric was based on datasets providing insight into economic stability, educational attainment, job diversity, and food accessibility. Indicators measuring relatively higher in any of these four components in a given CA would potentially ensure that the residents had other options for employment and nutrition if shellfish or salmon harvests declined due to OA. In more rural areas, such as some parts of interior Alaska, northwest Alaska, and southwest Alaska, adaptive capacity was comparatively low (Table 4).

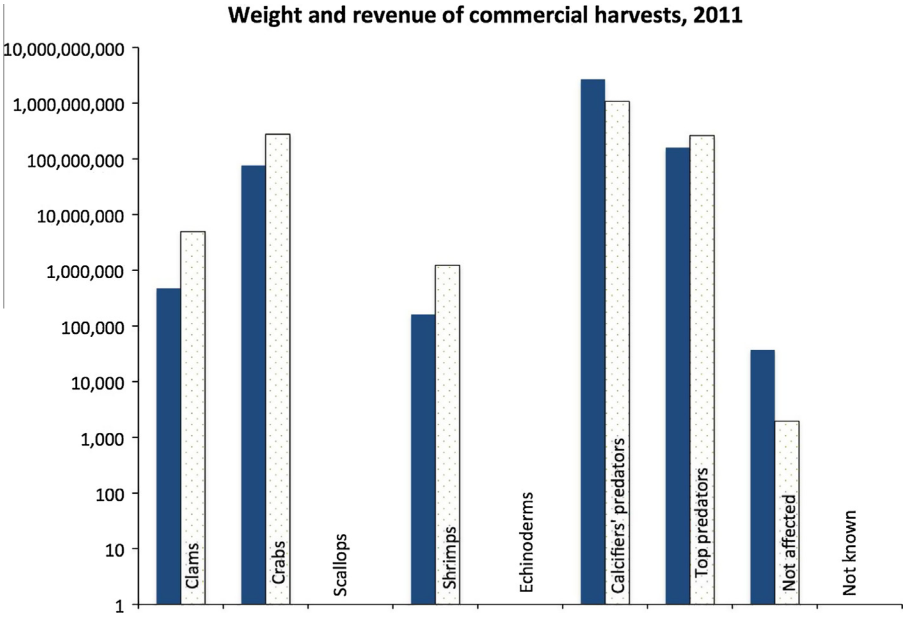

Fig. 7. Commercial harvest ex-vessel harvests (filled bars) in pounds and earnings (open bars) in U.S. dollars, by category, for 2011 based on ADF&G data. Scallops and echinoderms were unreported owing to confidentiality rules.

Table 3
For each major biological category, the proportion of species with reported data and the proportion of companies reporting data for a species in that category.

Category	Species reported (%)	Companies-species combination reporting (%)
Clams	50	85
Scallops	0	0
Urchins	0	0
Shrimp	50	93
Crabs	100	100
Calcifiers' predators	73	96
Top predators	70	98
Unaffected by OA	33	50
OA response unknown	100	100

Total risk

The total risk index brought together the risks from the hazard of OA, the extent fisheries' assets are exposed to it, and vulnerability of the human population. Table 4 shows the results for each CA, using the method described above. In general, southern Alaska is at greater risk from OA due to both dependence on OA-susceptible species for nutrition and income, and the rapidly forecasted change in chemical conditions (Fig. 4). Additional risk factors include being in a rural area with low job diversity, employment, and educational attainment, as well as high food costs.

Discussion

Hazard

Modeled present and future carbonate chemistry in the seas around Alaska represent average values modulated by global processes like atmospheric CO_2 uptake (Fig. 4), but the model's relatively coarse scale cannot simulate some of the features that greatly affect OA in Alaskan waters, such as sea ice melt, glacial discharge, river and groundwater runoff, and localized phytoplankton blooms or physical features. Indeed, local conditions observed are substantially affected in some locations by processes operating over short temporal and spatial scales that alter the carbonate system, as reviewed in Section 'Ocean acidification near Alaska'.

Biological responses

How, then, will projected changes to ocean carbon chemistry affect marine resources? Even though the western Arctic (CS and BS) may have the most rapid decline in aragonite saturation states, this area has limited direct connections to fisheries resources. However, the region is an important summer feeding ground for robust whale, walrus, and seal populations that are important to subsistence hunters along the coast as well as traditional cultural activities. On the other hand, the Bering Sea is predicted to progress more slowly toward increased OA, but it supports extremely valuable commercial and subsistence fisheries. Meanwhile, the loss of suitable habitat in a region may have unknown and cascading consequences for certain species in the future. As temperatures warm in the Bering Sea, subarctic species will likely shift northward (Cheung et al., 2013). However, water chemistry may have changed so that cooler habitats will also be characterized by markedly lower pH and Ω. In the most extreme scenario, these multiple stressors may combine to shrink or eliminate the environment appropriate for some species.

OA has been shown to have a substantial negative effect on red king and Tanner crab, particularly during the larval stages (Long et al., 2013a,b). Such declines in larval survival would likely affect overall population productivity through reduced recruitment, ultimately reducing the number of crabs available for commercial harvest. However, these early life stages occur from January to June and do not currently coincide with undersaturation events. More research on the effects of OA on other life history stages and their physiological responses is necessary to fully understand the effects it will have on crab populations throughout the year as well as other benthic calcifying organisms.

The impacts of OA on pelagic calcifying and non-calcifying organisms in the region are less clear. While there may not be a direct effect on certain pelagic finfish, such as walleye pollock, reflected in the limited impacts on growth and mortality, it is unknown how OA will affect the food supply of these fish or their

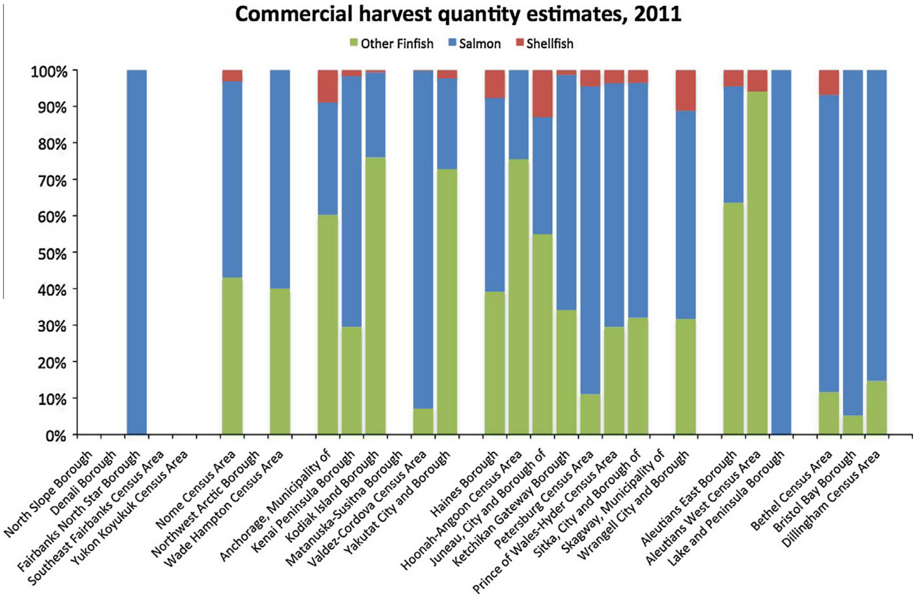

Fig. 8. Estimated proportions of 2011 commercial harvests associated with shellfish, salmon, and other finfish, calculated by weight and with confidentiality gaps estimated as described in the text. Gaps on the *x*-axis indicate no data for a given area.

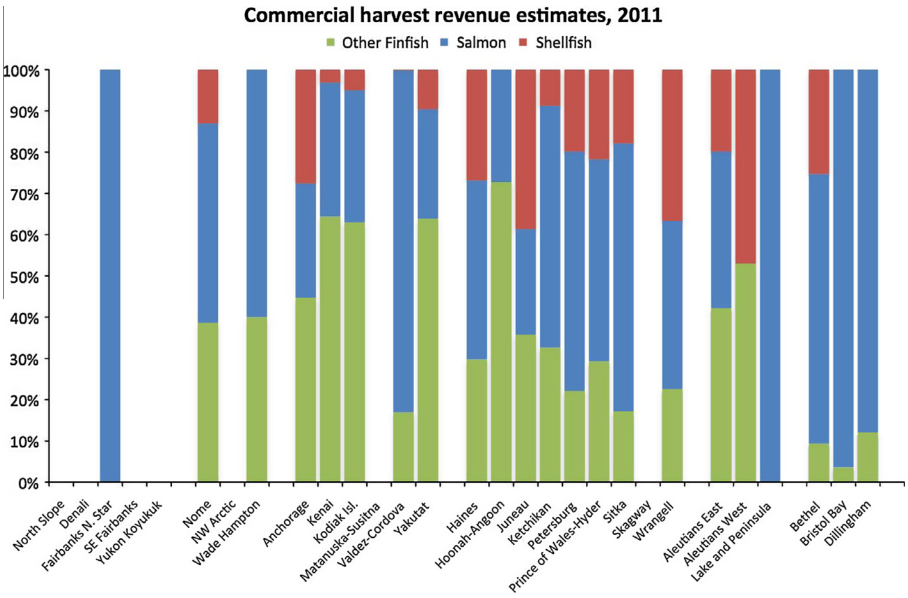

Fig. 9. Estimated proportions of 2011 commercial harvest revenues associated with shellfish, salmon, and other species, and with confidentiality gaps estimated as described in the text. Gaps on the *x*-axis indicate no data for a given area.

behavior. Walleye pollock also consume pteropods, but rely more heavily on copepods during early life stages before shifting to euphausiids as their major prey source (Brodeur et al., 2002; Dwyer et al., 1987; Moss et al., 2009). The impacts of OA on these lower trophic level organisms have yet to be resolved (e.g. Fabry et al., 2008). Because of these uncertainties and the varying degrees of organismal responses, there will likely be winners and losers as OA continues to worsen in the Bering Sea.

In addition to the potential impacts from OA-induced changes in the food web, Alaskan finfish species may also experience direct impacts from OA, as observed in some non-Alaskan species. For example, growth and survival were reduced at high CO_2 levels in newly hatched inland silversides (*Menidia berylinna*; Baumann et al., 2012); high CO_2 levels appeared to induce a range of morphological abnormalities in larval Atlantic cod without altering overall growth rate (Frommel et al., 2012); altered otolith growth (calcium carbonate ear bones; Checkley et al., 2009; Hurst et al., 2012; Munday et al., 2011) occurred in acidified conditions; and olfactory and auditory perception decreased (Dixson et al., 2010; Simpson et al., 2011). The mechanisms behind these processes or their overall effects are still not well understood, and it is possible that some Alaskan finfish species could experience these as well.

Whether indirect impacts due to trophic or habitat changes will affect Alaskan finfish is still also an open question. Copepods and krill are key links in polar food chains, and some evidence suggests that they might respond negatively to OA through changes in feeding, respiration, and excretion (e.g. Saba et al., 2012), while other studies identify mixed responses that implicate species adaptation or multigenerational acclimation (Fitzer et al., 2012). The lack of convergence of OA responses in copepods and krill prevent us from

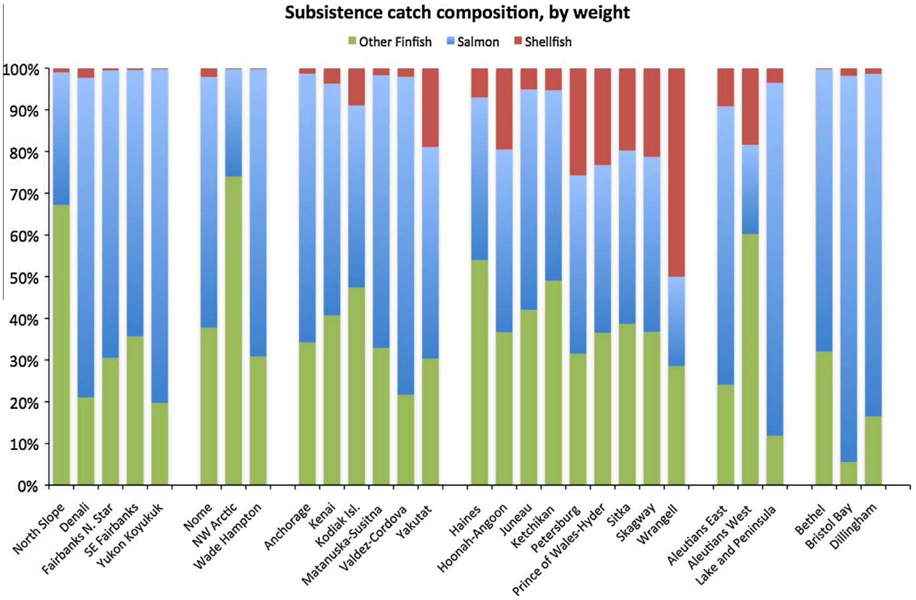

Fig. 10. Subsistence catch proportions by census area based on ADF&G data. Gaps on the *x*-axis indicate no data for a given area.

inferring any likely consequences on finfish that prey on these groups. Because of this, we treated salmon as an indirectly affected species, because evidence suggests that pteropods make up a significant and variable fraction of juvenile pink salmon diets (Armstrong et al., 2005; Aydin et al., 2005; Karpenko et al., 2007; Sturdevant et al., 2012). The projected negative effects on pteropods might represent a bottleneck in the production of this important species group. Unfortunately, while other harvested fishes are also known to consume pteropods (e.g. Moss et al., 2009; Sturdevant et al., 2012), there are insufficient data available to evaluate the general importance of this prey species to the marine fishes group as a whole. Similarly, while cold-water corals provide habitat for 42 of the 94 commercially harvested species in Alaska (J. Guinotte, personal communication), whether use of this habitat is obligatory or opportunistic is unknown, as is the degree to which changes in coral cover due to OA will translate into finfish populations. Additional research is necessary to evaluate the potential impact of OA to other marine species through these trophic and habitat pathways.

Of Alaska's many marine resource species, shellfishes appear to be the most directly influenced by OA (Long et al., 2013a,b). Declines in larval survival would likely affect overall population productivity through reduced recruitment, ultimately reducing the number of crabs available for commercial harvest. While older life stages are currently being exposed to these conditions in deeper waters and during seasonal events, the timing of reproduction in these species currently protects vulnerable larval stages from the detrimental effects of these seasonal pH minima. But the shoaling of the carbonate saturation depths and year-round persistence of undersaturated conditions will mean that crab larvae will be increasingly exposed to these conditions as OA progresses. More research on the effects of OA on other life history stages and their physiological responses is necessary to fully understand the effects it will have throughout the year on crab populations, as well as other benthic calcifying organisms.

The impacts that OA could have on Alaskan resource species through its effects on lower trophic level, pelagic calcifying and non-calcifying organisms could be more significant than the direct effects on some of those resource species. In this study, we chose to treat salmon as an indirectly affected species to explore the possibility of effects on Alaskan human communities if salmon is affected by this often-hypothesized route, rather than to make a definitive statement about OA's effects on salmon.

Human value of and dependence on OA-susceptible species

In Alaska, the principal connection between OA and the human community is via fisheries. Commercial fisheries take 97% of the wild resource harvest, while subsistence fishing produces about 2% of the total harvest of wild resource in Alaska, and sport fisheries take about 1% (Fall, 2012). Although the quantity of subsistence harvests are smaller than commercial harvests, subsistence fishing is very important to about 20% of Alaska's population, primarily Alaska Natives living in rural areas. On average, subsistence fisheries harvest provides about 230 lb of food per person annually in rural Alaska. In CAs where the average annual food cost is about twice that of Anchorage, such as Bethel, Bristol Bay, the Northwest Arctic Borough, and the Wade-Hampton CA, the nutritional (and, likely, indirect economic) benefits provided by subsistence harvests of all types of Alaskan species are immediate and critical.

The different weights applied to components of the adaptive capacity used in this study, while conservative, could be suspected to drive some of the trends observed. To judge how much the weighting affected the outcomes, we tested the effect of weighting the personal income variables in the adaptive capacity measure separately vs. weighting all seven components of adaptive capacity evenly, and we found that the effect of the weighting we applied was to slightly depress the adaptive capacity score ($R^2 = 0.97$). We also examined the effects of weighting shellfish-related numbers twice as much as salmon-related numbers. If the two taxa were weighted equally, exposure scores ($E_{H,E}$ and E_N) and vulnerability from nutritional dependence related to composition ($V_{S,N,C}$) were the only components of the final index that changed. The effects of this weighting assumption also ended up being a bit larger than the adaptive capacity assumptions, but overall, analysis results remained constant (Table 4). In that scenario, southern Alaska is still most strongly affected but the differences between census areas are more difficult to discern because there are more ties in the final index score. In the situation where shellfish and salmon are affected equally by OA, western Alaska is also more strongly at risk.

Table 4
Final scores for each census area and total ocean acidification risk index. Scores for each component of the final index (columns 3–10) are determined as described in the text. Low numbers correlate to lower risk for columns 3–11. The rank of final index indicates which region has the highest risk (#1) and which has the lowest (#29). When shellfish and salmon use are weighted equally or when the lowest future saturation state is assumed to represent the hazard (see text), the borough at highest risk changes, yet southern and western Alaska remain the regions with highest overall risk. When salmon and other finfish are weighted equally (see text), southern Alaska remains the region with highest risk.

Region	Census Area/Borough	$E_{H,E}$	E_N	$V_{S,N,C}$	$V_{S,N,Q}$	$V_{S,E,C}$	$V_{S,E,Q}$	V_C	H	Final index value	Rank of final index	Rank when shellfish/salmon equally weighted	Rank when salmon/finfish equally weighted	Rank when lowest future Ω_{ar} indicates most risk
North	North Slope Borough	1	1	1	2	2	3	4	1	1.65	29	29	27	29
Interior	Denali Borough	1	3	3	1	2	1	1	2	1.82	28	27	28	28
	Fairbanks North Star Borough	4	3	2	1	2	3	1	2	2.35	22	22	28	22
	Southeast Fairbanks Census Area	1	2	2	1	2	4	2	2	1.9	27	28	26	27
	Yukon Koyukuk Census Area	1	3	3	4	2	2	4	2	2.43	21	16	25	21
Northwest	Nome Census A Area	2	2	2	3	2	2	3	3	2.52	20	15	18	20
	Northwest Arctic Borough	1	1	1	4	2	1	4	3	2.31	24	24	23	24
	Wade Hampton Census Area	2	2	2	4	3	1	4	3	2.72	16	7	22	16
South Central	Anchorage, Municipality of	3	2	2	1	2	4	1	4	2.68	17	14	13	17
	Kenai Peninsula Borough	1	1	1	2	3	4	1	4	2.23	26	16	15	26
	Kodiak Island Borough	2	1	1	2	3	4	3	4	2.76	14	19	11	14
	Matanuska-Susitna Borough	1	2	2	1	2	4	1	4	2.35	22	16	23	22
	Valdez-Cordova Census Area	3	3	3	2	4	3	2	4	3.09	10	2	18	10
	Yakutat City and Borough	2	4	4	4	3	2	2	4	3.18	7	11	7	7
Southeast	Haines Borough	3	1	1	3	4	2	2	4	2.68	17	19	7	17
	Hoonah-Angoon Census Area	1	3	3	3	2	4	3	4	3.01	11	11	7	11
	Juneau, City and Borough of	4	1	1	1	2	3	1	4	2.81	13	22	12	13
	Ketchikan Gateway Borough	2	1	1	1	3	2	1	4	2.31	24	22	17	24
	Petersburg Census Area	4	4	4	3	4	1	2	4	3.47	5	8	6	5
	Prince of Wales-Hyder Census Area	3	4	4	3	3	3	3	4	3.51	3	13	3	3
	Sitka, City and Borough of	4	3	3	3	3	3	2	4	3.3	6	9	5	6
	Skagway, Municipality of	1	3	3	2	2	4	1	4	2.56	19	25	13	19
	Wrangell City and Borough	4	4	4	2	4	4	2	4	3.59	2	3	2	2
Southwest	Aleutians East Borough	2	4	4	2	4	2	4	4	3.51	3	3	3	3
	Aleutians West Census Area	3	1	1	2	2	2	3	4	2.76	14	19	1	14
	Lake and Peninsula Borough	4	4	4	4	4	3	4	4	3.92	1	1	7	1
West	Bethel Census Area	4	2	2	4	2	1	4	3	3.01	11	10	15	11
	Bristol Bay Borough	3	4	4	4	4	1	3	3	3.18	7	3	20	7
	Dillingham Census Area	3	3	3	3	4	1	3	3	3.18	7	3	20	7

Total picture of risk

Alaska's southern rural areas are likely at the highest risk from OA due to a confluence of factors, including: subsistence fishing for nearshore species like clams, crabs, and salmon, more rapid projected OA, lower industry diversity, economic dependence on fishery harvests, lower income, and higher food prices (Fig. 11). In particular, several areas in southeast Alaska (Wrangell City and Borough, Petersburg Census Area, and the City and Borough of Sitka) and southwest Alaska (Lake and Peninsula Borough) had scores of 3 or 4 for multiple components of the final index (Fig. 11). Even if urban areas have one or two strong risk indicators (e.g. Anchorage has risk associated with the high value of OA-vulnerable species and a faster projected change in ocean chemistry), they are offset by higher job diversity and higher overall regional income and job opportunities. This outcome is the same if adaptive capacity components are weighted evenly and if shellfish and salmon are weighted evenly. This trend, where more rural areas that have lower adaptive capacity are also more dependent on species highly susceptible to OA, matches the global trends observed by Cooley et al. (2012) for OA, Allison et al. (2009) for climate change, and Halpern et al. (2012) for ocean health and benefits overall.

Limitations of this study

Studies of human risk from global ocean changes are still at an early stage, and it is necessary to encompass a great deal of uncertainty in these studies. By focusing on OA, the path from marine biogeochemical change to human consequences seems fairly straightforward. However, there are uncertainties associated with the chemistry projections we used, the biological responses to OA, and the human community's response to changing marine harvests. Here we explore these factors and discuss them relative to the state of ocean acidification science.

Marine chemistry forecasts from a global ocean model are generally regarded as good representations of future conditions on the basin-scale, but for coastal systems, the accuracy of these forecasts is probably lower. As described in the previous sections, shallow, coastally influenced water near shore is subject to multiple pH-altering processes, and time series of pH and other carbonate system parameters in these areas are marked by spatial and temporal variability that is many orders of magnitude greater than that observed at open ocean time-series stations (e.g. Bates et al., 2012; Dore et al., 2009). This variability comes from biological production and respiration, upwelling, ice melt, and river runoff, none of which are captured in detail by the model projections used here, which show only future mean trends at the surface. Like other regions, it is very likely that Alaskan coastal marine systems already experience temporarily lower pH and saturation state as part of natural variability, and will continue to do so as the mean declines due to atmospheric CO_2. For now, the magnitude of pH and Ω variability experienced by most coastal systems is not well known until enough time-series data are gathered at nearshore locations.

In addition, the ways in which responses of individual organisms to OA translate into population- and ecosystem-scale responses are still unclear. We have only an initial but growing understanding of which aspects of OA are important for marine organisms: change in pH, carbonate ion level, saturation horizon depth, $p\text{CO}_2$, seasonal variability, phenology mismatch with seasonal life cycle cues or predator–prey interactions, biogeographic shifts away from appropriate benthic habitat, and so on. We assumed that negative responses at the individual level would translate to some degree of negative response in productivity at the population scale. Certainly this has been demonstrated with the study of bivalve mollusks, which originally were reported to calcify more slowly based on studies of two species (Gazeau et al., 2007; Kurihara et al., 2007), and which are now understood to display a range of negative population-scale responses to OA, including decreased reproduction, delayed development, and lower survival, as well as lower calcification (Kroeker et al., 2013b), and ecosystem-scale shifts away from calcifying species (Hall-Spencer et al., 2008; Kroeker et al., 2013a; Wootton et al., 2008). Meta-analyses support the inference that individual Alaskan mollusks are more likely than not to suffer from OA (Kroeker et al., 2013b), but whether whole populations of harvested clams and scallops are likely to decline as a result of OA is still not well known. Likewise, the population-scale or lifetime consequences of OA on red king crab and Tanner crab are still not known, despite the recent reports of individual effects (Long et al., 2013a,b). It is entirely possible that commercially or nutritionally important Alaskan species may be able to tolerate or adapt to lower pH, lower carbonate ion conditions, and this analysis does not account for that possibility. A different approach using individual-based models including their physiological responses would probably be necessary to do so. As more experimental data become available we will also likely understand which is more important for high-latitude species: the absolute or the relative change in pH and Ω. We will also be able to better estimate the consequences of indirect trophic and habitat effects, such as the salmon-pteropod scenario we explored here and the association of many Alaskan finfish with deep-water corals that we did not explore. Additional studies may also provide insight on whether market characteristics of harvests, like meat weight, appearance, and time to harvest, will change owing to OA.

To quantify risk based on current human use patterns of marine resources also assumes that humans' use of these resources is fixed, which it is not. But by incorporating multiple indicators of exposure (economic, nutritional) and of vulnerability (adaptive capacity, degree of dependence), which reflect more systemic aspects of the social–ecological system, we attempt to provide a snapshot of risk that has enough detail to encourage a harder look at the most important factors in subsequent studies. We also experienced a challenge in aligning the boundaries of socio-economic data with fisheries/ecosystem data, and then with oceanographic data: relevant datasets are collected using different geographic divisions, units (per capita vs. percent vs. total), and on different timescales (annually, every few years, decadally). Analysis of another vulnerability index indicated that scale affected the results of the overall index (Schmidtlein et al., 2008). We attempted to close gaps using average values where possible, and used the most updated information available in every case.

The indicators of adaptive capacity used here also have significant uncertainty associated with them. First, per capita income may be highly endogenous because it is built on fish income. Second, job diversity and total regional income in many areas may be endangered from declining oil production or bolstered by new events like natural gas exports. Because Alaska's economy is an energy export economy, climate change could affect the entire economy via climate policy: a carbon tax would depress the value of exported oil. (Conversely, limiting CO_2 emissions via a carbon tax or other means could decrease OA and its effect on the marine resources being studied.) All of these factors add uncertainty to any measurement of adaptive capacity.

Building a more resilient social–ecological system in Alaska

Alaskan commercial fisheries have a long history of opportunistically switching to different species based on availability and marketability, suggesting the socio-economic system may have some ability to adapt to future conditions. An example of this is the

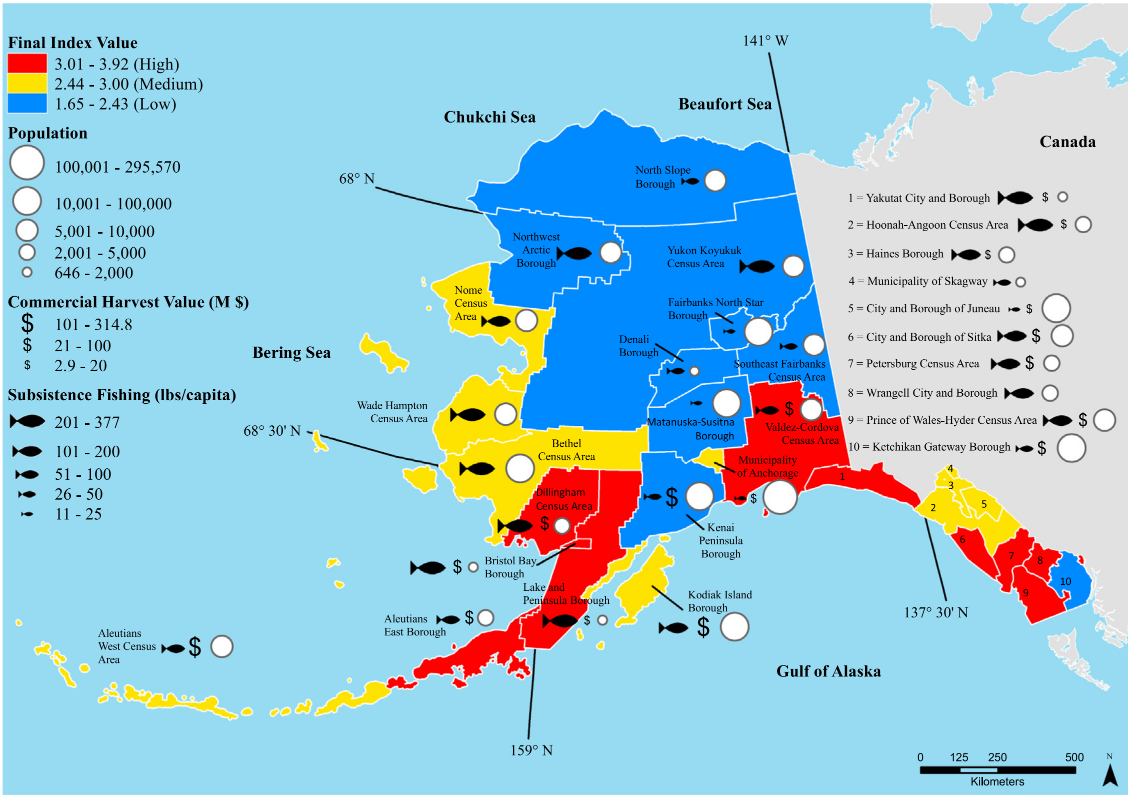

Fig. 11. Individual components of the final ocean acidification risk index for each census area.

shrimp fishery, where shrimping in the Gulf of Alaska was a major commercial and subsistence resource until the 1980s when an ecosystem change (e.g. Anderson and Piatt, 1999) caused the fishery to completely crash. Communities throughout the region were able to shift to ground/finfish fishing rather quickly.

A far more ominous example, though, is what occurred in Prince William Sound, where herring supported a major fishery until the early 1990s. It has been suggested that the 1989 Exxon Valdez oil spill initiated a decline in herring abundance (Thorne and Thomas, 2008). However, other analyses suggest that the population collapse in 1993, four years after the spill, was triggered when poor nutritional condition of herring, brought about by low zooplankton production, increased the susceptibility of herring to disease, possibly exacerbated by the stress of low winter temperatures (Pearson et al., 1999). Regardless of the underlying cause, the herring population has yet to recover and the fishery in Prince William Sound has been closed for 17 of the last 23 years (Pearson et al., 2012). The loss of this fishery cost the region millions of dollars, thousands of jobs, and the loss of a reliable subsistence food source. Many communities, especially those that were heavily dependent on the herring fishery, went into sharp decline and some small towns and village shut down completely.

The example of the region's herring loss, taken together with the community index data presented here (Table 4; Fig. 11), clearly demonstrates the need for commercial diversification, particularly in southeast and southwest Alaska. This may involve looking to other sectors, like exploiting other resources (e.g. fur seals, gold, timber, oil, and natural gas) or encouraging other industries. Many towns and villages throughout the state are facing multiple challenges, including rising food and energy costs, loss of revenue from declines in oil and gas production, and declining populations. OA may be yet another challenge to these communities, adding another stressor to a region already at socio-economic risk.

Conclusions

The outcomes from this risk assessment concerning ocean acidification's potential to affect Alaska's fishery sector can inform policies and guide future scientific studies of the social–ecological system that depends on marine resources. While we recognize that the index developed here is an intermediate step toward our full understanding of the economic and societal consequences of OA, it does provide valuable insights on social vulnerability. Community- or state-scale policies offer numerous opportunities to combat regional processes (e.g. fertilizer runoff, atmospheric emissions of nitrogen species) that worsen acidification, but only when the contributing factors are well understood. In this study, we sought to identify areas of the social–ecological system that are most vulnerable (i.e. the components of the final index with highest scores); the entire risk of the system could be decreased by the application of localized policies designed to build adaptive capacity, decrease exposure, or distribute risk where those factors were dominating the degree of vulnerability. From this analysis, it is evident that risk assessments offer more thorough decision-relevant information because they provide insight into the interaction of social, economic, and natural components instead of just one facet.

In Alaska, plans to confront OA can be made that address the natural and the social system by dealing with aspects of the hazard, exposure, and community sensitivity. To address the hazard, which is primarily associated with the natural environment, continued monitoring of conditions in Alaska's nearshore regions is an important response. This will add important regional specifics to the general picture currently available from ocean model projections, and identify which oceanographic processes are most important in driving regional OA. To address exposure to the hazard, productive responses would be most effective in southern and western Alaska, where human dependence on OA-susceptible marine resources is highest (Fig. 11). These responses might encourage diversification of fisheries activities, exploiting a broader range of species, not just those that are OA-susceptible. Ultimately, the strategies to mitigate and adapt/prepare for OA impacts must be developed by the communities themselves. To foster participation in such planning, residents and other stakeholders in vulnerable communities must first be educated about this emerging environmental challenge, then be permitted to develop response strategies that incorporate community values and are context- and situation appropriate. To reduce community vulnerability, factors that lower adaptive capacity, such as low income, nutritional status, educational attainment, or industry diversity, must be addressed. These factors create vulnerability to many environmental and social problems beyond OA, so addressing them could provide overall benefits. In Alaska, where dependence on marine resources is strong, traditional, and very deep-rooted, attempting to reduce risk from OA or any other marine-related type of global change simply by decreasing dependence on marine resources may be a poor fit. Instead, users and decision makers must consider the elements that contribute to risk, as well as those that offset it, and attempt to choose a path that optimizes these yet retains traditional and contemporary uses of these valuable marine resources.

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