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Consequences of spatially variable ocean acidification in the California Current: Lower pH drives strongest declines in benthic species in southern regions while greatest economic impacts occur in northern regions

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ABSTRACT

Marine ecosystems are experiencing rapid changes driven by anthropogenic stressors which, in turn, are affecting human communities. One such stressor is ocean acidification, a result of increasing carbon emissions. Most research on biological impacts of ocean acidification has focused on the responses of an individual species or life stage. Yet, understanding how changes scale from species to ecosystems, and the services they provide, is critical to managing fisheries and setting research priorities. Here we use an ecosystem model, which is forced by oceanographic projections and also coupled to an economic input-output model, to quantify biological responses to ocean acidification in six coastal regions from Vancouver Island, Canada to Baja California, Mexico and economic responses at 17 ports on the US west coast. This model is intended to explore one possible future of how ocean acidification may influence this coastline. Outputs show that declines in species biomass tend to be larger in the southern region of the model, but the largest economic impacts on revenue, income and employment occur from northern California to northern Washington State. The economic consequences are primarily driven by declines in Dungeness crab from loss of prey. Given the substantive revenue generated by the fishing industry on the west coast, the model suggests that long-term planning for communities, researchers and managers in the northern region of the California Current would benefit from tracking Dungeness crab productivity and potential declines related to pH.

1. Introduction

The oceans are experiencing warming, acidification, eutrophication, and other changes that are modifying marine ecosystems (Halpern et al., 2008; Ekstrom et al., 2015); these modifications have consequences for human communities that rely on living marine resources. Much of the research focused on the impacts of novel stressors has investigated the responses of individual species (e.g., Cooley et al., 2015; Dueri et al., 2016; Vanderplancke et al., 2015). However, understanding how these changes scale up to impact ecosystems and ecosystem services, such as fisheries catch and revenue, is critical to setting research priorities and making strategic marine resource management decisions. Ecosystem scale research has begun to identify broad geographic regions most at risk from modifications of the environment (Kaplan et al., 2010; Ainsworth et al., 2011; Cheung et al., 2011; Barange et al., 2014). However, impacts on human communities often depend on localized ecological change, making it critical to understand changes at a finer geographic scale (Ekstrom et al., 2015).

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Human communities are place-based and benefit from distinct sets of species. Thus, spatially heterogeneous variation in climate change impacts on those species can have socio-economic consequences that vary across communities. Methods to understand the consequences of marine ecosystem change require an interdisciplinary approach (Bai et al., 2016) that includes oceanographic conditions (such as temperature and/or pH) at high resolution, spatially explicit responses of the ecosystem to those conditions and the dependencies of local human communities on marine resources (Allison et al., 2009).

Ocean acidification (OA), caused by increasing global carbon emissions, is a stressor with both spatial and temporal variability that has the potential to restructure marine systems (Griffith et al., 2011; Branch et al., 2012; Le Quesne and Pinnegar, 2012; Marshall et al., 2017). Both calcifying and non-calcifying species have been shown to respond directly to changing pH (Branch et al., 2012; Kroeker et al., 2013; Busch and McElhany, 2016). Ocean carbonate chemistry varies globally (Orr et al., 2005; Friedrich et al., 2012) and some regions are more at risk from OA than others because of a natural occurrence of low pH water from upwelling that is expected to be exacerbated by the effects of OA (Feely et al., 2016). Such regions include eastern boundary currents like the California Current large marine ecosystem (Feely et al., 2008; Gruber et al., 2012).

The California Current is an upwelling system with high spatial variability in oceanographic conditions (King et al., 2011) and seasonally low pH in nearshore environments (Feely et al., 2008; Gruber et al., 2012). Upwelling occurs in spring and summer, bringing up low pH waters that create a temporal window of exposure to low pH that is expected to worsen with OA (Hauri et al., 2013). Latitudinally, the California Current can be divided into three regions (King et al., 2011). The northern region, defined by the area north of Cape Mendocino (or Cape Blanco) is defined by strong winter storms and substantial freshwater inputs. The regions south to Point Conception, California, and then beyond Point Conception, experience higher levels of upwelling than in the north, as indicated by the Bakun Cumulative Upwelling Index. Feely et al. (2016) report the lowest surface pH in the central region and a model by Hauri et al. (2013) projected this region to have the most variable pH levels (range = 7.85–8.15; $\sigma_{pH} = 0.1$) and the lowest surface pH most months of the year. Though species in this system may have adapted to these heterogeneous conditions (Pespeni et al., 2013), the natural occurrence of low pH waters can be problematic because future declines may push pH beyond species' physiological tolerance thresholds (Fabry et al., 2008; Feely et al., 2008; Gruber et al., 2012). The oceanographic heterogeneity in the California Current will lead to heterogeneous exposure to low pH waters, and thus spatial heterogeneity in ecosystem changes.

The California Current supports a diverse food web and a multi-million-dollar fishing industry. The direct ex-vessel revenue from fisheries in the US portion of the ecosystem was worth over $450 million in 2013 (PacFIN, 2013). Fisheries catches and species composition are localized in time and space (Kaplan et al., 2013b). For instance, fisheries in Washington State are dominated by Dungeness crab (*Metacarcinus magister,* Cancridae), sardine (*Sardinops sagax*, Clupeidae), Pacific hake (*Merluccius productus*, Merlucciidae), and shrimp (family Pandalidae), while ports off southern California catch market squid (*Doryteuthis opalescens*, Loliginidae), mackerel (family Scombridae), sardine, anchovy (*Engraulis mordax*, Engraulidae) and nearshore urchins (*Mesocentrotus* spp., Strongylocentrotidae) (PacFIN, 2013). Given the variability of target species and total landings between ports in the California Current (Kaplan et al., 2013b) and heterogeneity of oceanographic conditions (King et al., 2011; Hauri et al., 2013; Feely et al., 2016), changes in catch from ocean acidification are likely to be regionally different, based on localized changes in organism responses. Basin-wide impacts have been projected in the California Current (Kaplan et al., 2010; Marshall et al., 2017), the southeastern Australia marine ecosystem (Griffith et al., 2011) and for the UK (Fernandes et al., 2016). To our knowledge, no work has estimated how OA may impact fisheries at finer spatial scales, such as the port-level.

Here we explore spatially heterogeneous impacts of ocean acidification on species and fisheries in the California Current. We employ oceanographic predictions from a Regional Oceanographic Modeling System (ROMS) model, forced by an earth system model (GFDL-ESM2M) under climate scenario RCP8.5; an Atlantis end-to-end marine ecosystem model (Fulton et al., 2011); and an economic input-output model (Leonard and Watson, 2011). We projected the state of the ecosystem in the 2060 s and described spatial variation in the marine species and human communities at risk. The value of ecosystem models such as this is in long term strategic management and planning (where path dependency means that actions now may influence the utility of measures into the future) as well as research prioritization; thus our work identifies where future research, monitoring and management focus is needed by exploring the potential consequences of pH changes and vulnerabilities for port revenue, income and employment in US west coast communities.

2. Methods

2.1. Overview

We used an ecosystem model to investigate the impacts of ocean acidification in the California Current and consequences for fishing communities along the US west coast. Outputs generated by a fine-scale ocean model provided physical forcing for the Atlantis ecosystem model for the present and 50 years in the future. Outputs from Atlantis were then passed to an economic input-output model developed for the west coast of the US (IO-PAC; Leonard and Watson, 2011). A schematic diagram representing the modeling approach can be found in Appendix A (Fig. A1). Because the IO-PAC model and high-resolution revenue data were only available for the US portion of the model, we focused our economic analysis on the US west coast (i.e., excluding Canada and Mexico). We focused on the 17 US port groups on the outer coast (excluding Puget Sound) used by the Pacific Fisheries Information Network (PacFIN) to aggregate data and avoid issues of disclosure of confidential information (Table 8-1 of Appendix A in PFMC, 2004). For all 17 port groups we simulated changes in catch, revenue, income and employment.

2.2. Summary of Atlantis model

We used the spatially explicit end-to-end ecosystem model Atlantis (Fulton et al., 2011) to simulate food web dynamics and fisheries. Atlantis represents ecosystem dynamics with three components: (i) an oceanographic sub-model (ii) an ecological sub-model and (iii) a human dynamics sub-model (Fulton et al., 2004a,b). Extensive documentation of the Atlantis modeling framework, for both the California Current and other ecosystems, can be found in previous publications (Fulton et al., 2004a,b; Kaplan et al. 2010, 2013a). Therefore, we briefly summarize the most recent version of the Atlantis model developed for the California Current (Marshall et al., 2017), including all three sub-models, highlighting changes we made explicitly to investigate spatial impacts of OA.

The physical domain of the Atlantis model is represented by polygons, which are defined by depth ranges and by longitudinal and latitudinal breaks. Our model includes 88 spatial polygons that span the entire domain of the California Current, from the northern extent of Vancouver Island, Canada and south to Punta Eugenia, Baja California, Mexico. Longitudinal polygon boundaries were based on bathymetry with breaks at 50 m, 100 m, 200 m, 550 m and 1200 m and then finally at the 200 nautical mile Exclusive Economic Zone (EEZ; Fig. 1). These breaks were chosen based on a mixture of bathymetric and biological information (representing: nearshore shelf, deeper shelf, shelf/slope break; see Appendix S1 in Marshall et al., 2017). Depth ranges of boxes within the model match the depths used to define bathymetric breaks.

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