Title

Communicating Ocean Deoxygenation: Developing Recommendations for Communicating Ocean Deoxygenation to California Policy Makers

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Developing Recommendations for Communicating Ocean Deoxygenation to California Policy Makers

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Executive Summary:

A problem associated with anthropogenic climate change that is often overlooked by policy makers is the loss of oxygen within the ocean, referred to as ocean deoxygenation. This problem has the potential to cause immense harm to the oceans, the organisms found within, and the resources and ecosystem services the oceans provide for humans. Despite the threats to our ecosystem and well-being, ocean deoxygenation is relatively unknown to policy makers and the public. Although studies have documented the loss of oxygen in the oceans over the last 50 years, it was only within the last 10 years that the term "ocean deoxygenation" was even created, cementing the connection between oxygen loss and anthropogenic climate change. Few efforts have been made to communicate this issue outside the scientific community, but an effort to address ocean deoxygenation must be made soon if we want to reverse or mitigate its effects. California has experienced large percentages of oxygen loss over the past few decades: Monterey Bay lost 39.9% of its oxygen between 1998 and 2014 at 250-400 meters depth, and the Southern California Bight lost 21% of its oxygen at 300 meters depth between 1984 and 2006 (Levin et al., 2018). This paper reviews ocean deoxygenation awareness, the successful campaign to communicate ocean acidification, and outlines communication recommendations to raise awareness of this issue among California legislators and policy makers in hopes of influencing mitigation policy and practices. These recommendations were created based on successful communication methods used in communicating the similar climate change-related issue of ocean acidification. Ocean acidification is a comparable example of an ocean health issue that continues to be communicated to policy members at the state and federal level. Ocean acidification and ocean deoxygenation are related to climate change; both exhibit complex mechanisms that can be simplified into succinct messages, and both became established in the literature within the past two decades. The communication model used for ocean acidification will serve as a good base from which to develop recommendations for communication about ocean deoxygenation. This communication recommendation framework is meant to help establish a California-based case study of how to approach communicating ocean deoxygenation that can be used to guide future communication methods at the federal level.

Part I: Ocean deoxygenation

What is ocean deoxygenation?

The term "ocean deoxygenation" refers to a decline in dissolved oxygen levels in the oceans due to anthropogenic climate change (Keeling et al., 2010), but also includes eutrophication-induced oxygen loss (Rabalais et al., 2014). This currently occurs in all of the world's oceans, mainly at bathyal depths (100 – 600 meters), but not in all locations. Declining levels of oxygen have been documented beginning in the mid-20th century (Keeling et al., 2010) but were only recently described and recognized as a climate-driven threat to the health of the oceans (Keeling et al., 2010). Ocean deoxygenation can lead to a decrease in biodiversity and productivity, the displacement of many organisms, and the disruption of important biological processes (Breitburg et al. 2018). Most living organisms (except for anaerobic microbes) need oxygen to survive. Therefore, ocean deoxygenation is considered one of the most significant changes that is happening to the oceans right now (Diaz & Rosenberg, 2008; Breitburg et al. 2018; Rabalais et al., 2014). More recently, ocean deoxygenation has been defined as “the loss of oxygen caused by anthropogenic influences, including excess carbon dioxide emission and nutrient inputs (Levin, 2018).

Many terms exist that refer to low levels of oxygen in the ocean that differ from ocean deoxygenation. Hypoxia and dead zones are terms that are essentially synonymous with each other (NOAA, 2017). Hypoxia refers to a shortage of oxygen for life processes, often defined as an oxygen concentration of <63 μmol kg^{-1} (<2mg L^{-1} or <1.4 mL L^{-1}) (Levin, 2018). If oxygen concentrations in hypoxic zones decrease they may become anoxic. Anoxic zones are areas of the ocean that have an absence of measurable oxygen (Levin, 2018).

Beneath upwelling regions, there are naturally occurring zones in the ocean that have extremely low oxygen levels. Referred to as oxygen minimum zones (OMZs), these zones are found in the East Pacific Ocean, Northern Indian Ocean and off West Africa, usually at 100 – 1200 meters depth (Helly & Levin, 2004). The dissolved oxygen concentrations present in oxygen minimum zones are so low (< 20 μmol kg^{-1}) that only species specially adapted to live in low oxygen environments can survive there. Consequently, many fish and invertebrate species are excluded. As oxygen levels decline, intolerant taxa are forced into shallower or deeper depths to avoid oxygen minimum zones (Körtzinger et al., 2012).

The rise of ocean deoxygenation science

Coastal hypoxia and dead zones have been documented for decades, dating back to the mid-20th century; however, historically these events have been closely tied to eutrophication as the main driver (Diaz and Rosenberg 2008). Eutrophication occurs when nutrient runoff (mainly nitrogen and phosphorus) from land-based sources stimulates the growth of algae, usually causing algal blooms. When these algal blooms die, microbes consume large amounts of oxygen through decomposition and aerobic respiration, which can cause hypoxic zones to form and may eventually lead to anoxic, or dead zones (Breitburg et al., 2018). Some of these land-based sources include agricultural fertilizer and untreated sewage runoff.

It wasn’t until the 2000s that scientists connected widespread open ocean hypoxia with anthropogenic climate change (Bopp et al., 2013; Keeling et al., 2010). In 2010 Keeling et al. coined the term “ocean deoxygenation,” calling it “a potential serious consequence of global warming” (Keeling et al., 2010). Keeling also noted that predictive models at the time projected a potential decrease in global dissolved oxygen by 1-7% over the next 100 years and explained the potential of this decline to expand the size of naturally occurring oxygen minimum zones (Stramma et al. 2008). At that point in time, ocean deoxygenation was only starting to garner attention and not much research had been done; however, Keeling et al., (2010) did generate interest in further research by suggesting the relationship between climate change and ocean oxygen loss. The large body of literature on manifestations of ocean deoxygenation generated since the Keeling et al., (2010) publication is synthesized in Levin, (2018).

Later studies showed that the release of greenhouse gases (GHG) into the atmosphere through the burning of fossil fuels is warming the planet and oceans, affecting oxygen distributions. As water temperatures rise, oxygen becomes less soluble, reducing the amount of oxygen that can dissolve in the ocean through diffusion, mixing, and wave action at the surface. This reduction in solubility is responsible for roughly 15-16% of global ocean oxygen loss, and 50% of oxygen loss within the upper 1000 meters of the surface (Levin, 2018).

Warming ocean waters also create more stratified ocean layers. Ocean layers naturally form, with colder, dense water sinking to the bottom. Differences in density not only create a layering of the ocean, but also encourage the movement of these layers, causing underwater currents to form. Climate change is causing these layers to become more distinct, which reduces vertical mixing of the water column, resulting in reduced oxygen concentrations throughout the entire ocean (Keeling et al., 2010; Levin, 2018)

Warmer water also increases the respiration rates of animals. Therefore, as the ocean warms up, ocean animals need more oxygen to survive. In fact, in 2016 it was estimated that a 3-degree Celsius water temperature increase in the Sargasso Sea will increase oxygen consumption rates by 50% (Brewer & Peltzer, 2016). Organisms also have a critical oxygen partial pressure below which they exhibit reduced metabolic functions, known as a p_{crit} value, although this value is unknown for most species. Dungeness crab, an important commercial fishery species in California, exhibits a P_{crit} value of 2.69 mL/L (Johansen et al., 1970), well above the oxygen conditions present in expanding oxygen minimum zones that threaten species such as these.

In 2017, Schmidtko et al. published a research paper estimating that the global ocean has lost 2% of its total oxygen since 1960 (Schmidtko et al., 2017). Oxygen decline in the oceans is not uniform and changes depending on depth and latitude. Different ocean basins or local regions have lost differing amounts of oxygen over the past 70 years (Schmidtko et al., 2017; Levin 2018), implying that while the global ocean is at risk of deoxygenation, some areas are more at risk than others and may need to be targeted for mitigation techniques.

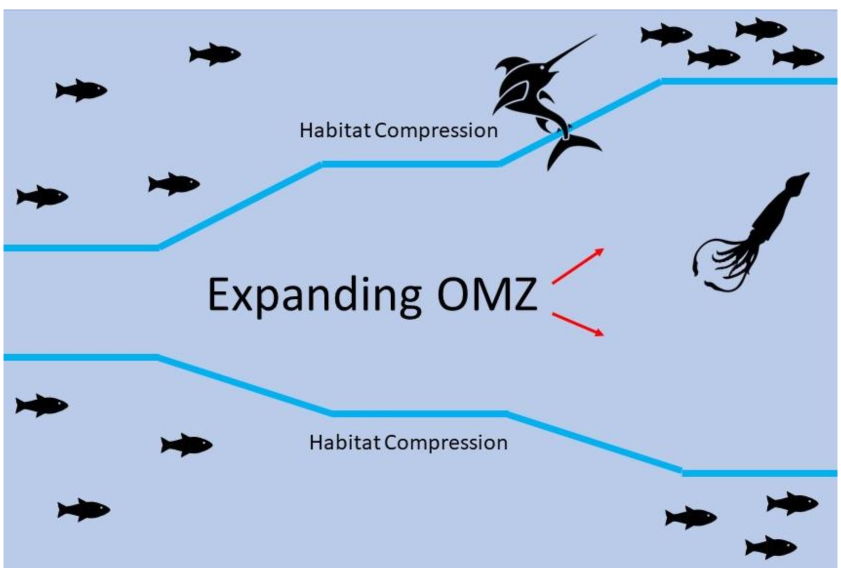

Figure 1. Expanding OMZs force many aerobic organisms above or below the OMZ threshold, making them more vulnerable to predation.

Ocean oxygen changes associated with changes in the climate are expected to have a large impact on animals living around OMZs. Recent work shows that OMZs are expanding as oxygen levels decrease (Stramma et al., 2008). Pelagic and mesopelagic fish species that live on the boundary of OMZs are likely to be forced to live in shallower waters or reduce their depth of vertical migration (Gilly et al., 2013). Those organisms that live on the upper boundary of the

OMZ (typically around 100m) will be more concentrated towards the surface, as decreased oxygen will prevent them from diving into the expanded hypoxic conditions. For example, a study in 2012 found that blue marlins in the eastern tropical Atlantic restricted their vertical movement to the top 100 meters of the ocean in the presence of an OMZ, while individuals regularly dive to below 200 meters in an area without an OMZ (Stramma et al., 2012)**.** This suggests that the OMZ is forcing these blue marlin, a species that needs a lot of oxygen to support its high metabolism and respiration, to the surface through habitat compression. Likewise, it is estimated that organisms that live below or on the lower boundary of the OMZ (typically around 1200m) will be forced to live at lower depths and under more crowded conditions (Gilly et al., 2013).

Although the effects of expanding oxygen minimum zones on fish, elasmobranch and invertebrate populations are still being studied, habitat compression can potentially have an impact on commercial and recreational fisheries (Körtzinger et al., 2012, Prince et al., 2010), making it easier for fisherman to catch a large population of fish that are corralled into a smaller living space, but also making it easier for these species to be preyed upon by their predators. However, some organisms are well adapted to living in these hypoxic conditions, such as the Humboldt squid.

While the greatest amount of documented oxygen loss has occurred in OMZs, there are many other regions of the ocean (North Pacific, Southern Ocean, and South Atlantic) that have lost considerable amounts of oxygen (Levin, 2018). Overall, the world's oceans have lost two percent of its oxygen in the past 50 years, but this loss is much higher in some areas (Stramma et al., 2017, Levin 2018).

Climate-driven ocean deoxygenation is happening in concert with other mechanisms impacting oxygen in the ocean, most notably, coastal eutrophication (Rabalais et al., 2014). Now, the effects of climate-driven ocean warming, and deoxygenation are also contributing to these coastal hypoxic zones, although it is unclear to what extent. Altieri and Gedan, (2014), analyzed the impact that climate change will have on already established dead zones and suggest that it is contributing to an increase in dead zones around the world, stating "Evidence is accumulating from some ecosystems that the effects of climate change are sufficiently strong enough to further increase the severity of dead zones, even if the rates of eutrophication are kept in check or reduced." Climate driven changes such as decreased oxygen solubility, increased stratification, and increased respiration are the major contributors to these dead zones. As in the open ocean, coastal warming creates stratified layers in these coastal zones, while also making oxygen less soluble and increasing the respiration rate of organisms. Warming can increase the extent and intensity of coastal hypoxia and cause earlier onset and longer duration of seasonal hypoxia. It is important to understand that coastal zones are experiencing multiple stressors leading to hypoxic zones and that fixing only one stressor may not ultimately solve the problem.

Current actions to address ocean deoxygenation

Increased interest in researching ocean deoxygenation led to the establishment of the Global Ocean Oxygen Network (GO_2NE) in 2016. The Global Ocean Oxygen Network (GO_2NE) is an internationally recognized network established by the Intergovernmental Oceanographic Commission (IOC), an organization within the United Nations Educational, Scientific and Cultural Organization (UNESCO). The GO_2NE network aims to provide a "global and multidisciplinary view of deoxygenation, with a focus in understanding its multiple aspects and impacts" (Global Ocean Oxygen Network, 2016). It is comprised of representatives from 11 different nations. Both the GO_2NE website and its news site, www.ocean-oxygen.org, provide information on ocean deoxygenation, although it is not presented it a format easy for the casual reader to understand. GO_2NE is the first organization of its kind with a focus on ocean deoxygenation.

Despite this observed loss of oxygen, interest from international leaders in deoxygenation has been disconcertingly low. The first three Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) fail to mention a decline in ocean oxygen concentrations and primarily focus on sea level rise as the main change in the ocean driven by climate change. (IPCC, TAR WG, 2001; IPCC SAR WG, 1996; IPCC, Working Group I, 1990). The IPCC Fourth Assessment Report includes a small section on ocean oxygen concentrations, mentioning its fluctuations and variance, but draws no clear conclusion of the mechanisms behind these fluctuations (IPCC, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007). The IPCC Fifth Assessment Report contains a short (four paragraphs) section dedicated to oxygen in the oceans that does mention the term "deoxygenation" and addresses the possible and likely connection to climate change. However, ocean deoxygenation in this IPCC report is very much overshadowed by other related global change issues such as ocean acidification and sea level rise (IPCC, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014). More recently, as a part of the Paris Agreement, only one nation, Mauritania, listed ocean deoxygenation as a concern related to climate change in their nationally determined contribution (Gallo et al., 2017).

Perhaps the biggest public response to ocean deoxygenation came in 2018 following the Breitburg et al. publication in Science, "Declining oxygen in the global ocean and coastal waters," (Breitburg et al., 2018). This paper reviews the drivers, implications, and potential responses to ocean deoxygenation in coastal and open waters. This paper's message was quickly picked up by various media outlets, bloggers, and social media sites. Three months after its publication, Altmetric ranked it in the top 5% of all research outputs scored by them, and the 29th most popular article published in *Science* based on the Altmetric scale, scoring higher than 99% of its peers (https://www.altmetric.com/details/31264072). This article prompted media responses from new outlets like Newsweek, The Independent, The Guardian, and Smithsonian.com, as well as 1782 tweets, 31 posts on Facebook pages, and 21 blog posts.[1] This piece generated more attention than any previous ocean deoxygenation paper and led to more prominent appearances of the topic in the popular media.

[1] Although it is not entirely clear, the popularity of this paper may have been a result of an Associated Press piece and information sharing by a social media influencer. A social media influencer is a user that has well established credibility and tout a large audience to share information.

The International Union for the Conservation of Nature (IUCN) is planning to publish a comprehensive review of ocean deoxygenation in the near future. The ultimate goal of this review is to consolidate known information about deoxygenation, looking into causes, impacts, consequences, and solutions. This will be the first review of its kind for ocean deoxygenation. It comes at a time when deoxygenation is just starting to become more relevant and recognizable to scientists and world leaders as an ocean threat. It will raise awareness among NGOs, IGOs, governments, and other non-academic entities.

Why should we care about deoxygenation?

The consequences of ocean deoxygenation are complex and can be somewhat unclear when identifying ecosystem service impact. A lack of oxygen can impact organisms on an individual level - it can kill them or cause changes in morphology and behavior. At the population level it can drive changes in migration patterns, and at the community level it can cause loss of biodiversity. These impacts manifest at all depths of the ocean. Most of the long-term monitoring of oxygen concentrations happen in the upper 500 meters. In Southern California, the California Cooperative Oceanic Fisheries Investigations (CalCOFI) dissolved oxygen data has been collected quarterly since the 1960s. Analysis since the 1980s reveals approximately a 20% decrease in oxygen on the outer shelf and upper slope (200-300 meters) (Bograd et al. 2008, 2015). Time-series data from the benthos is less available mainly due to budget and availability and accessibility of the correct equipment.

It is well documented that smaller organisms are more tolerant of low oxygen, possibly because of their large surface area to body ratio (Levin, 2003). Although there is some debate in the scientific community as to whether body size is exclusively influenced by oxygen availability, it has been suggested that reduced oxygen will lead to reduced body size of larger organisms (Daniel & Cheung, 2017) or select for small species (Levin, 2003). If the former is true, reduced body size from ocean deoxygenation will yield fewer offspring and perhaps influence species on an evolutionary timescale. Oxygen availability is also closely tied to other biological functions, such as vision and reproduction. Vision has high oxygen requirements, and recent research hypothesizes that under hypoxic conditions, vision may be impaired, leading to behavioral changes in marine organisms that need vision to see and escape from predators, which may change the distribution of these organisms (McCormick & Levin, 2017). Reproduction is impacted because it is an energy intensive process. If an organism allocates more energy towards respiration in an attempt to secure more oxygen, it is possible that energy for gamete production will diminish (Breitburg et al., 2018).

Humans are most likely to feel the results of ocean deoxygenation in relation to how it impacts organisms at the community or ecosystem levels. Ocean deoxygenation is changing the physical chemistry of the water, causing the expansion of OMZs and leading to habitat compression. As OMZs expand it is likely that squids' predatory range will increase, at least to the point where OMZ conditions fall below the threshold where predators like the Humboldt can survive (Gilly et al., 2013). Usually, organisms living in these conditions will be more aggregated and potentially more vulnerable to predation from other organisms and fishers, which may lead to overexploitation and a collapse of the fishery.

OMZ expansion may also lead to a decrease in catch. A study in 2015 found that catch per unit effort (CPUE) for demersal fish species on the west coast of the United States was related to oxygen concentrations; as oxygen concentrations decrease, the CPUE decreases (Keller et al., 2015). Measuring the direct impact that ocean deoxygenation has on coastal or open-ocean fisheries is difficult to do because many factors influence catch, but these ocean deoxygenation will likely result in a negative impact.

Precisely how hypoxic conditions impact fisheries is hard to predict in comparison to the effects of other stressful conditions. One study showed that estuaries and semi-enclosed seas under hypoxic stress do not see a decrease in fisheries' landings compared to fisheries under other stressful conditions, such as a high nitrogen load (Breitburg et al., 2009). Assessing the impact that ocean deoxygenation has on fisheries is challenging because fisheries, and fishery management, rely on accurate scientific data on species distribution, stock size, recruitment, and many other facets of a species' livelihood. Oxygen impacts all of these properties and so the impact of oxygen loss on these variables must be studied further to predict the full impact of ocean deoxygenation. Even with the difficulties in measuring direct impact, ocean deoxygenation is a problem that will reach a wide range of ocean organisms and will most likely have negative consequences on California fisheries (McCormick et al., unpublished).

Many of California's most lucrative commercial fishery species may be at risk from ocean deoxygenation. The physiological tolerance of low oxygen (P_{crit} value) for most of these species is unknown, but oxygen tolerances are published for two such species. The Dungeness crab, which generated in $83 million in landings in 2016 (CADFW, 2017), has a published P_{crit} value of 2.69 mL/L (Johansen et al., 1970). The Shortspine thornyhead, another important fishery species that generated $2 million in landings in 2016 (CADFW, 2017), has a published P_{crit} value of 0.5 mL/L (Lai & Graham, 1992). Many California fishery species that normally live in OMZs, such as Sablefish, species that live on the edge of OMZs, such as Swordfish, and species that live outside of OMZs, such as Red urchins, are all commercially important fishery species (McCormick et al., unpublished). The majority of these species have never been evaluated for their low oxygen tolerance, and therefore ocean deoxygenation is often overlooked in informing fishery management plans. This lack of information emphasizes the unknowns in how ocean deoxygenation precisely impacts ecosystem services.

Possibly the most important community impact to acknowledge is the sheer loss of biodiversity that will come as a result of ocean deoxygenation. Some species are more tolerant of low oxygen than others. These species are typically smaller in size and have adaptations to survive hypoxic conditions. As ocean deoxygenation intensifies, animals will die either as a direct result of lower oxygen availability, or through increased predation or disease from living in a more crowded zone. In fact, the California Current saw a decline of 63% of its mesopelagic fishes between periods of high and low oxygen over the past decade (Koslow et al., 2011). These fish are important food sources for many other organisms in the ecosystem, and it is likely that a decline like this will impact the food web in some way.

Ocean deoxygenation awareness

Ocean deoxygenation is recognized at the international level, federal level, and state level in California to varying degrees and with varying terminology. Table 1 outlines the efforts made at these organizational levels to raise awareness about ocean deoxygenation, making it clear that efforts to raise awareness and increase research are happening on an international scale among scientists, and revealing a large gap on local impacts and any effort to educate policy makers or the public.

Table 1. International, federal, and California State efforts to raise awareness of ocean deoxygenation.

	International		**Federal (USA)**		**State (California)**	
	Effort	**Audience/Goal**	**Effort**	**Audience/Goal**	**Effort**	**Audience/Goal**
Advocacy Organizations	GO$_2$NE (IOC-UNESCO)	International Policy/ provide a global outlook on ocean deox to better understand it			West Coast Ocean Acidification and Hypoxia Science Panel (2013) ---------- Ocean Acidification and Hypoxia Science Task Force (2016)	West Coast State governments/ create recommendations on how to address ocean acidification and hypoxia (focus on OA) ---------- CA government/ create recommendations on how to address ocean acidification and hypoxia (focus on OA)
Reports	<u>IPCC reports</u> Special Report on Oceans and Cryosphere (2019) AR4 (2007) AR5 (2014)	National governments/ consolidate climate science, identify future risks, recommend responses	Climate Science Special Report (2017)	U.S. government/consolidate climate science, identify future risks, recommend responses	West Coast Ocean Acidification and Hypoxia Science Panel Report (2016)	West Coast State governments/ recommendation on how to address ocean acidification and hypoxia
Conferences/ Meetings	Deoxygenation in the oceans: past, present and future (2010) California, USA ---------- Ocean deoxygenation and implications for marine biogeochemical cycles and ecosystems (2011) Toulouse, France ---------- Low oxygen environments in marine, estuarine and fresh waters (2014) Liege, Belgium ---------- Ocean ventilation and deoxygenation in a warming world (2016) London, UK ---------- Ocean deoxygenation drivers and consequences (2018) Kiel, Germany	International, scientists/ investigate history and future projections on ocean deox ---------- International, scientists/ discuss possible impacts of ocean deox ---------- International, scientists/ investigate new insights into ocean deox ---------- International, scientists/ evaluate possible impacts on ocean deox ---------- International, scientists/ focus on past, present, future state of oxygen on differing scales and what drives ocean deox				
Legislation			Harmful Algal Bloom and Hypoxia Research and Control Act (1998), and subsequent amendments	U.S. coastal states/ create a working group to recommend how to address algal blooms and coastal eutrophication	AB 2139 Ocean Protection Council: Ocean Acidification and Hypoxia (2010) ---------- SB 1363 Ocean Acidification and Hypoxia Reduction Program (2010)	CA government/ establish a CA OAH task force ---------- CA government/ establish a CA program to reduce OA and hypoxia

Relationship to ocean acidification

Another major consequence of excess carbon dioxide emissions is ocean acidification, which like ocean deoxygenation is expected to have major impacts on marine ecosystems. Over the last decade the subject of ocean acidification has risen from relative obscurity and become widely recognized by scientists, educators, policy makers and the public. The next section of this paper will address successful communication strategies used to raise awareness of this problem and emphasize the impact that ocean acidification has on the oceans. Although this paper will not cover the specific mechanisms behind ocean acidification, it is important to understand that the comparison and development of communication strategies between ocean deoxygenation and ocean acidification is valid, in part because they are inherently linked through respiration. Areas of the ocean that exhibit hypoxia (such as OMZs and coastal dead zones) are often also carbon dioxide (CO_2) maximum zones. Warming causes increased respiration rates of most aerobic ocean organisms, which increases the amount of oxygen consumed and carbon dioxide that is released by these organisms through respiration. The comparison is also justified because both ocean acidification and ocean deoxygenation are human-influenced issues resulting from excess carbon dioxide emissions and both were established in the scientific literature only a few decades ago (the first appearance of the term "ocean acidification" occurred in 2003 (Caldeira & Wickett, 2003), and the first appearance of the term "ocean deoxygenation" dates to 2010 (Keeling et al., 2010). Chart 1 shows the number of publications that contain the specific phrase "ocean acidification" or "ocean deoxygenation" over the past two decades. Both topics are complex, and both are influencing ocean health. Given this, the recommendation strategies for communicating ocean deoxygenation to California policy makers addressed in this paper have their basis in the recommendation strategies used for ocean acidification's rise to prominence.

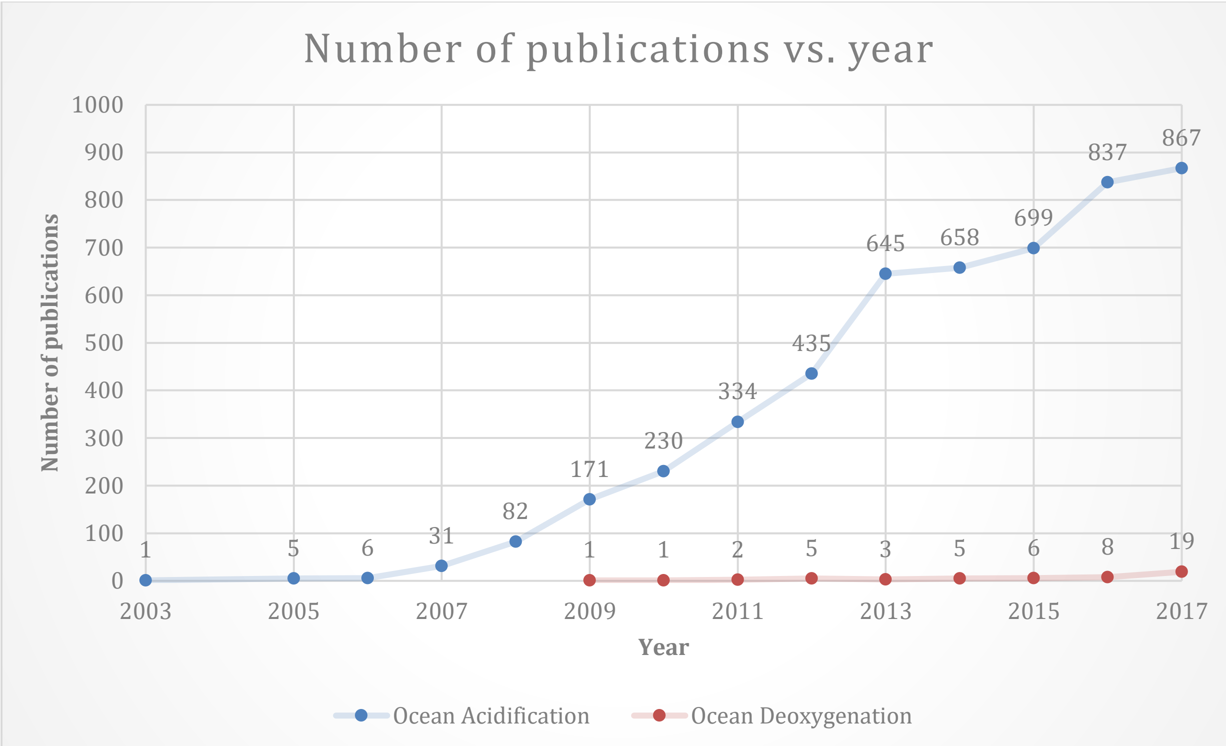

Chart 1. The number of scientific publications per year that include the specific phrase "ocean acidification" or "ocean deoxygenation," as listed in the Web of Science Core Collection database (https://apps.webofknowledge.com/).

Part II: Ocean acidification

Ocean acidification actions

Scientific interest and observation led to the establishment of ocean acidification (OA) in the scientific literature and began generating real interest in the scientific community. The first time the term "ocean acidification" was used in a scientific context was in 2003 with the publication of "Anthropogenic Carbon and Ocean pH," in Nature (Caldeira & Wickett, 2003). This paper defines OA as "…carbon dioxide released into the atmosphere as a result of the burning of fossil fuels [that] will eventually be absorbed by the ocean, with potentially adverse consequences for marine biota." Although this definition has many different iterations, it has remained relatively constant over the last decade. The IPCC Fifth Assessment Report defines OA as "a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean" (IPCC, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014). In both of these definitions, it is the specificity of the addition of carbon dioxide from the atmosphere which constitutes OA. The IPCC report further defines *anthropogenic* ocean acidification as reduced pH condition as a direct result of human influence.

Shellfish hatchery industry workers became involved in OA research and awareness because of an oyster larvae crisis. OA started to garner attention in the Pacific Northwest between 2005 and

2009, when mass die-offs of oyster larvae were observed in oyster hatcheries in Oregon and Washington State, most notably the Whiskey Creek Shellfish Hatchery (Barton et al., 2015), which supplies oyster larvae for oyster growers throughout the State of Washington. Research into these die-offs revealed ocean acidification to be the main culprit. Low pH, or more acidic, ocean water can dissolve the calcium carbonate shells of oysters and other shellfish (known as calcifiers), preventing shellfish larvae from properly forming a shell and making them more vulnerable to conditions that may lead to their death (Adelsman & Binder, 2012). Washington's shellfish industry is commercially important. Annually it generates $270 million and supports 3,200 jobs. These losses of oyster larvae motivated a response to the threat of OA by the Washington State and federal governments (Adelsman & Binder, 2012).

To support more research to address OA, in 2009 the federal government passed the Federal Ocean Acidification Research and Monitoring Act (FOARAM). This act establishes the Interagency Working Group on Ocean Acidification, which includes representatives from many different government agencies, to research and monitor the possible impacts of ocean acidification on ocean resources and ecosystems (Interagency Working Group on Ocean Acidification, 2018.). This act also established an ocean acidification program in the National Oceanic and Atmospheric Administration (NOAA). In 2010 the Ocean Acidification Task Force was formed at the federal level and published a list of recommendations for the interagency working group to best address OA and accomplish the goals set by the FOARAM act.

The story of the Whiskey Creek Hatchery and other incidents that involved shellfish die offs in the Pacific Northwest created interest in NGOs and philanthropic funders. The Ocean Conservancy and the Ocean Foundation became involved with ocean acidification in 2009 with funding from a few different philanthropic organizations, including the Education Foundation of America (EFA), which had personal interests in OA. Following the release of the 2009 film, "A Sea Change," the first documentary on ocean acidification, the EFA funded programs within the Ocean Conservancy and the Ocean Foundation, both non-profit ocean advocacy organizations, to try to drive action at the state and federal level by elevating the story of ocean acidification. As such, the Ocean Conservancy and the Ocean Foundation were the first NGOs to develop dedicated ocean acidification advocacy programs. The Ocean Conservancy's work with OA focuses on community impacts of OA and works with community members to tell their stories. They also help draft legislation and aim to create champions within congress to advocate for OA legislation. The Ocean Foundation works with educating donors, while also working directly with policy makers to draft legislation. They also advocate for OA awareness on an international stage.

California wanted to act preventively as well. In 2010 the Ocean Acidification Impacts on Shellfish Workshop was held in California. This workshop convened as it became clear that lower pH waters were impacting west coast shellfish fisheries. This workshop aimed to "encourage cooperation between scientists, shellfish growers, fishermen, and environmental managers," ("SCCWRP - Ocean Acidification Workshop," 2010). A major result of this workshop was the creation of the California Current Acidification Network (C-CAN). C-CAN represents a collaboration of a variety of stakeholders, including scientists, fishers, and resources managers mentioned above. The network's goals are to standardize OA measurements and data collection practices, but also to make West Coast OA data publicly available (California Current Acidification Network, 2013). C-CAN represents one of the first attempts to bring a variety of stakeholders together to acknowledge and address OA, and may have influenced early political support for OA research on the West Coast (Kelly, 2017). Many similar OA networks have since been established with similar goals, including the Northeast Coast Acidification Network, the Southeast Ocean and Coastal Acidification Network, and the Alaska Ocean Acidification Network.

To take concrete steps and identify suitable state level solutions, Washington State convened the Blue Ribbon Panel on Ocean Acidification in 2012. The panel was created by Governor Christine Gregoire and consisted of a number of different stakeholders, including scientists, industry representatives, policymakers, community representatives, and tribal representatives. The panel was charged with reviewing scientific data about OA, identifying gaps and needs in terms of research and monitoring, identifying ways to better facilitate cooperation between impacted parties, and developing recommendations to respond to OA. The panel published its recommendations in 2016, along with a scientific report about OA in Washington State in 2016. The recommendations include a number strategies to combat OA, including reducing carbon dioxide emissions, reducing the influence of land-based contributions to OA, and educating and engaging stakeholders, the public, and policy makers on the importance of addressing OA (Adelsman & Binder, 2012).

The looming threat of ocean acidification in the Pacific Northwest sparked interest in researching the possible impacts of OA in California coastal waters. In 2013 the Ocean Protection Council (OPC), a governmental body in California charged with protecting California's coastal and ocean ecosystems, commissioned the West Coast Ocean Acidification and Hypoxia Science Panel. This panel, made up of representatives from Washington, Oregon, California, and British Columbia, studied the effects of ocean acidification (OA) and its relationship with hypoxia. In 2016 the panel published a report outlining a set of recommendations to address the OA problem (Chan et al., 2016). Although this panel includes hypoxia in its name and considerations, the report clearly is weighted towards recommendations and findings related to OA rather than hypoxia, even stating, "this panel's products are more focused on OA because our understanding of the effects of OA and its interaction with hypoxia is only beginning to grow," (Chan et al., 2016).

These results plus advocacy from local and national funders, experts, and NGOs influenced two pieces of legislation that were passed in California in 2010. AB 2139 (Williams. Ocean Protection Council: Ocean Acidification and Hypoxia) gave the OPC the ability to develop an Ocean Acidification and Hypoxia Science Task Force (in a similar vein to the West Coast Ocean Acidification and Hypoxia Science Panel) to create recommendations to address OA and hypoxia and inform relevant policy in California. SB 1363 (Monning. Ocean Protection Council. Ocean Acidification and Hypoxia Reduction Program) allows the OPC to develop an Ocean Acidification and Hypoxia Reduction Program in the hopes of mitigating the effects of these issues. Currently no other policy exists in California to address ocean deoxygenation or hypoxia.

During this early period of action, the science evidence was evolving to show that OA is working in conjunction with other stressors, including ocean warming, ocean deoxygenation, and changes in food supply that have compounding negative effects. Recent studies have turned to focus on this multi-stressor view point and efforts are being made to predict how these stressors together will impact the ocean in the future. One of the first times this multi-stressor viewpoint was emphasized was in 2012 at the Symposium on the Ocean in a High-CO_2 World (2012 Symposium on the Ocean in a High-CO2 World, 2014). Since then, the emerging trend among ocean scientists is to identify how these multiple stressors work together. A publication in *Oceanography* in 2015 suggests that the consideration of multiple stressors is important for management and mitigation as well as increasing public awareness (Breitburg et al., 2015).

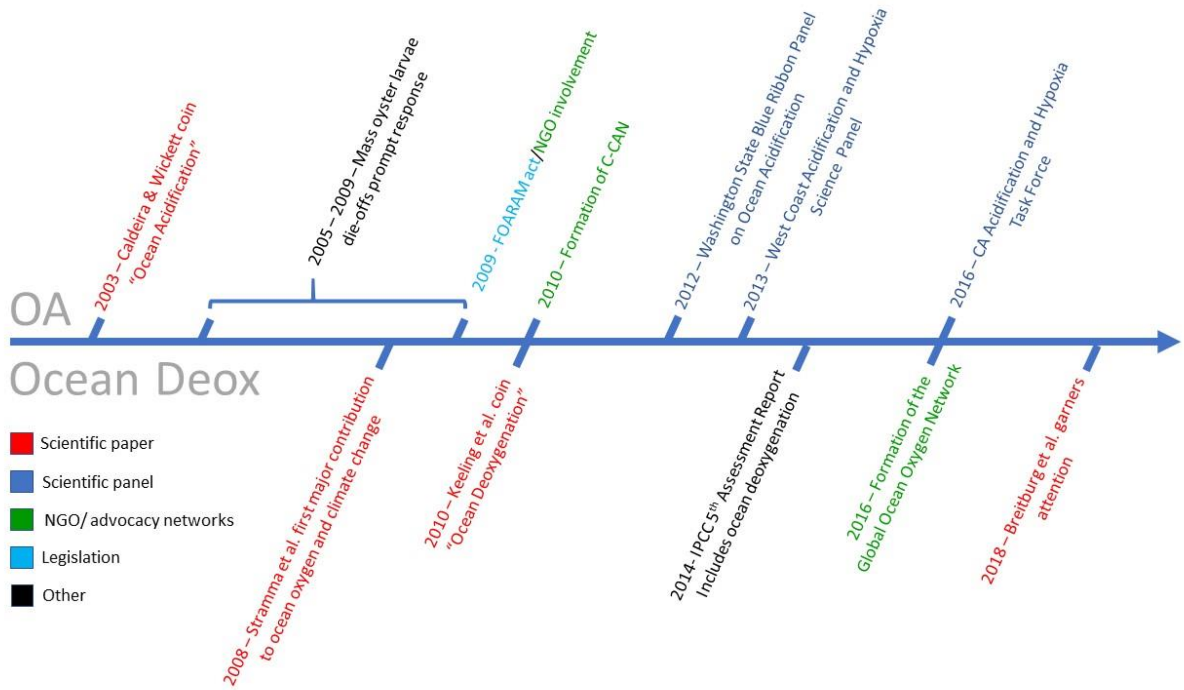

Figure 2. A timeline of major contributions to ocean acidification and ocean deoxygenation awareness.

Educating policy makers about OA

Efforts to communicate the threat of ocean acidification and ways to address it have taken many forms over the last decade. Different communication strategies were employed to address different audiences, all with the intent of raising awareness, garnering a concerned group of people, and encouraging community, state, and federal changes to mitigate the impacts of OA. Some of these audiences include community members or members of the general public, NGOs, scientists, and policy makers. This section will review some of the methods used to communicate OA during the start of the OA awareness campaign in the early 2000s, some of which continue today. In any effort to communicate a complex scientific topic it is important to identify your audience and your goals. All of the communication efforts outlined here started by identifying an audience and developed around speaking to that audience's interests and abilities. Although this section does not cover all the communication method used for OA, it covers the initial efforts that influenced OA awareness throughout the nation.

Many of these communication efforts also stemmed from a desire to avoid failed communication efforts to raise awareness of climate change, which was not as effective as most communicators and educators hoped for in the early 2000s. Moser and Dilling (2012) point out the four major failings in communicating climate change:

1. "Inspiration with information." The idea that people will become motivating to take action if they have more information and understanding of the issue.
2. "Motivation by fear." The idea that making people fear the possible impacts of climate change will motivate action.
3. "One size fits all." The idea that communication should focus on the science behind climate change no matter who the audience is.
4. "Mobilization through mass media." The idea that the most effective way to reach audiences is through mass communication techniques, such as television and internet campaigns.

Climate change communication efforts also failed to make influencing policy makers and policy decisions a priority, rendering many of their efforts moot without the policy to support them (Moser and Dilling, 2012).

Keeping these failings in mind, communication efforts for ocean acidification employed different techniques. At the forefront were communication efforts in the shellfish industry whose workers felt the direct impact of OA on their livelihoods and well-being. Communication strategies began with creating a narrative, most notably, the story of the Whiskey Creek shellfish hatchery. This hatchery provides oyster larvae to the majority of oyster growers in Washington State, but suffered mass larval die-offs of 75-80% between 2006 and 2008 (Kelly et al., 2014). Working with local scientists, it was determined that an increase in carbon dioxide from upwelling off the coast created acidified water and caused the large increase in mortality. Once the problem was identified, larval populations in the hatchery began to rebound through the use of monitoring equipment and a reduction of the use of acidified water in the hatchery during spawning events. During this process, the hatchery operators were vocal about happened to the hatchery and the steps they were taking to address it, in an effort to raise awareness and prove that mitigation practices can be successful. This story transformed ocean acidification from an ocean chemistry problem, which might seem too remote to interest non-scientists, to a human-impact story – a problem that impacts the way we live our lives. This narrative was critically important in creating change, and especially in communicating the importance of OA to policy makers. The Whiskey Creek story helped kick-start a response to ocean acidification (Kelly et al., 2014).

Many different organizations have formed with the intention of communicating OA and making its science available and understandable including C-CAN, the Ocean Acidification Information Exchange, the Global Ocean Acidification Observing Network (GOA-ON), and COMPASS. Various NGOs also have a focus on OA, including the Ocean Conservancy, the Ocean Foundation, Oceana, and The Nature Conservancy. As OA continues to get recognized world-wide as a threat to our ocean health and human well-being, more and more organizations continue to form with a focus on OA research and awareness. They provide platforms from which to distribute information about OA as well as resources with which to launch more concentrated efforts to create change through legislation and action.

The first two NGOs to focus on OA advocacy were the Ocean Conservancy and the Ocean Foundation. These organizations took slightly different approaches to communicating ocean acidification with slightly different audiences, though their methods are similar in many respects.

In the early 2000s, anthropogenic climate change was a topic of heated political debate. Given this, the Ocean Conservancy structured their approach to OA advocacy by highlighting it as an environmental problem separate from climate change. Anthropogenic climate change and OA are driven by the same general mechanisms. Namely, carbon dioxide released into the atmosphere generates a greenhouse effect, trapping heat and warming the planet. Carbon dioxide from the atmosphere enters the ocean, chemically reacting with the water, decreasing the pH and creating a more acidic environment. Yet, the Ocean Conservancy chose to talk about OA while avoiding the terms “climate change” or “global warming” as much as possible.

In the early 2000s few politicians were eager to take a stance on climate change. Climate change was a partisan issue whose primary messaging to policy makers focused on the science behind it rather than its impacts to humans and ecosystem services. To avoid a partisan divide, the Ocean Conservancy worked towards evoking a response to ocean acidification by focusing on the human aspect. The Ocean Conservancy helped coordinate “dear colleague” letters which conveyed personal stories from local communities to their representatives. Applying a “human face” to ocean acidification not only made it more approachable to non-scientists, but also made it clear that it is an issue of importance to congressional constituents and therefore one to which policy makers should pay close attention to. In framing ocean acidification, emphasizing human impacts on a local level was of huge importance.

Another way that ocean acidification was (and still is) introduced to policy makers was through “message bills.” These bills are pieces of legislation that are broadly structured and are written with the understanding that they are likely to fail. Message bills are constructed to convey a particular message and promote an action related to ocean acidification. They force representatives to take a stance on the issue. These message bills reveal representatives who may be good targets to focus on when lobbying for funding, but also give ocean acidification more exposure and help garner support and co-sponsors for future bills. The message bill approach is not meant to influence an immediate response in legislation but rather to build relationships and spread messaging over a longer period of time. Bills like this are submitted frequently by congressional offices working with the Ocean Conservancy. Through lobbying, community storytelling, and message bills, the Ocean Conservancy hoped to identify and create “champions in Congress,” to spearhead the ocean acidification legislation and support all OA related bills.

The Ocean Foundation started their efforts in for OA awareness in 2004, first educating donors about the issue to help secure funding. Since then, their work focuses on working directly with policy makers to draft meaningful and impactful legislation at the state level to mitigate ocean acidification, different from the Federal messaging bills strategy adopted by the Ocean Conservancy. The Ocean Foundation focuses messaging on the impact that OA will have on the nations economy, claiming that the economic argument pulls a lot of weight in government. Much of their work today for OA advocacy is also on the international stage.

Similar to the Ocean Conservancy, the Ocean Foundation focuses a lot of effort on creating "champions in Congress." These champions not only co-sponsor OA bills and can be counted on to vote for any OA related legislation, but they also serve an important purpose educating their peers. According to the Ocean Foundation, politicians educating fellow politicians can be more effective than lobbying by scientists or environmental advocates. In establishing the first champions for the OA causes, the Ocean Foundation targeted individuals who stood to gain by taking on the role, either because of those whom they represent, a sense of pride in helping the environment, or a desire to establish their legacy as leading this movement within government.

The Ocean Foundation also focused on telling a story, by establishing a protagonist and following the simple formula of "and, but, therefore." No matter where in the world you are, a story such as this can be established to convey the important of addressing ocean acidification. Keeping the story simple is important because not everyone needs to understand the process to be passionate about it. Knowledge does not equal action, attitude equals action.

The creation of various working groups, including the Washington State Blue Ribbon Panel on Ocean Acidification, the 2013 West Coast Ocean Acidification and Hypoxia Science Panel, and the 2016 Ocean Acidification and Hypoxia Science Panel were intended to bring multiple different stakeholder groups together, but also to fill in knowledge gaps and interpret new scientific findings. Although we know a lot more about ocean acidification than we did ten years ago, work is still being done to research how specifically ocean acidification impacts the ocean at community and ecosystem levels and how this impact translates directly to economic impacts. These working groups aim to provide answers to broad questions that are important to policy makers, including: Who will be affected by ocean acidification next? How will this impact the economy and my constituents? And, what can we do to address it? Answering these questions will drive legislative decisions to mitigate ocean acidification, but as simple as these questions sound, they are hard to answer.

Educating the public about OA

Educating the public is an important step in creating more knowledgeable constituents to influence a policy response. Educating the public also encourages non-scientists to become familiar with ocean acidification and take steps to change their own behavior to play a role in mitigating OA. A number of different outlets are used to communicate ocean acidification to the public. As more scientific data become available about OA, websites, films, social media platforms, scientific and educational institutions, and training organizations have developed to present this information in manners that non-scientists are able to understand.

COMPASS is training organization that helps "marine scientists effectively share their knowledge in the public discourse and decision-making," ("COMPASS | Our Mission & History," 2018). It and began in 1999. This organization does not solely focus on OA trainings, but as early as 2004 it began to help OA scientists frame their work in an understandable way. Organizations like COMPASS train staff at scientific and educational institutions, such as aquariums and museums, to be more effective in communicating ocean acidification.

Similar training programs exist for climate change as a whole, including the National Network for Ocean and Climate Change Interpretation (NNOCCI) and Made Clear, the Maryland and Delaware Climate Change Education Assessment and Research program. Both of these programs aim to educate climate change communicators and teachers about the best practices to use when communicating the complex processes of climate change, while establishing accurate scientific interpretation. Although these programs don't focus on ocean acidification explicitly, they are associated with OA and are some of the more popular climate change training programs throughout the country.

Probably the easiest way for members of the public to locate and understand information on ocean acidification is through the internet. Many NGOs that work on ocean acidification have an accompanying website to consolidate information about OA and to talk about the work they are currently doing. Well-designed websites, along with the use of easy-to-understand infographics, blog posts, and videos are all effective ways of disseminating information. This is made all the easier with the use of social media. Most NGOs, scientific institutions, and policy makers have some type of social media platform from which they can share information. Social media also provides a way to get in touch directly with the people providing the information and gives a direct line to key players in marine conservation and policy.

Translating OA solutions to ocean deoxygenation

The best way to mitigate or stop ocean deoxygenation is to reduce the use of greenhouse gases that contribute to climate change. However, this is a monumental task. There are also a number of smaller actions that can contribute to mitigating ocean deoxygenation while large emissions cuts are negotiated. The West Coast Ocean Acidification and Hypoxia Science Panel released their recommendations for addressing ocean acidification in 2016. These recommendations are written on how to address ocean acidification, and not hypoxia, however many of these recommendations can be easily translated to use for ocean deoxygenation by simply switching the focus of the recommendation. Table 2 outlines these possible translations. The table represents how simple it can be to use already established recommendations and strategies developed for another ocean health issue as a framework on how to solve related issues. Recommendations for ocean acidification are especially relevant since ocean acidification and ocean deoxygenation are so closely related.

Table 2: Recommendations to address Ocean Acidification by the West Coast Ocean Acidification and Hypoxia panel adjusted for ways to address ocean deoxygenation.

OAH recommendation	Adjusted for Ocean Deoxygenation	Reasoning
Rec. 1. Reduce local pollutant inputs that exacerbate OAH.	Reduce local pollutant inputs that exacerbate oxygen declines	Excess nutrients from land-based sources encourage eutrophication which can create coastal dead zones. Local sources of nitrogen, phosphorus, and organic matter should be reduced or eliminated.
Rec. 2. Advance approaches that remove CO_2 from seawater.	Advance approaches that add or maintain oxygen concentrations in seawater	Novel ideas are needed to mitigate oxygen loss. Science should be done that focuses on ways to reduce or maintain oxygen levels in the ocean.
Rec. 3. Revise water quality criteria	No equivalent	Reasonable dissolved oxygen concentrations is already a water quality criteria in California. Water entering the ocean should not be below 10% of what occurs naturally in that area.
Rec. 4. Reduce co-occurring stressors on ecosystems.	Reduce co-occurring stressors on ecosystems that can increase vulnerability to hypoxia or exacerbate effects of hypoxia.	Dissolved oxygen is impacted by many external factors, including temperature, pH, excess nutrients from upwelling and land-based sources, pollution, habitat degradation, overfishing, and species invasion.
Rec. 5. Advance the adaptive capacity of marine species and ecosystems.	Incorporate oxygen requirements in fishery and marine protected area management and environmental impact statements.	Oxygen requirements are overlooked in commercial fishery management plans in California. Oxygen should be considered when creating fishery regulations and marine spatial planning including marine protected areas – which impacts fisheries and biodiversity.
Rec. 6. Establish a coordinated research strategy.	Establish a coordinated research strategy.	Ocean deoxygenation research should be driven and focused on management needs to build a comprehensive data set to inform policy.
Rec. 7. Build out and sustain a West Coast monitoring program that meets management needs.	Create a California climate change monitoring program that meets management needs.	Include ocean deoxygenation in OA and temperature monitoring for climate change to assess vulnerability, variability, etc. use this monitoring to develop predictive models.
Rec. 8. Expand scientific engagement to meet evolving management needs.	Expand scientific engagement to meet evolving management needs.	Ocean deoxygenation is an emerging field. A network of scientists, educators, and communicators should exist to disseminate information.

Part III: Communication recommendations for ocean deoxygenation

Below I present recommendations for communicating ocean deoxygenation to California State policy makers. All of these recommendations are based on the success of OA communication strategies used to influence OA legislation at the state and federal level. Because of the success of OA communications to influence policy decisions and create widespread interest among educators and communicators, it can be viewed as a model for ocean deoxygenation. Strategies can be adjusted in their scope to become more localized to California, and in their messaging to "Just like you and me, most ocean animals need oxygen to survive," to achieve our goal in influencing policy decisions. California legislators are the target audience because they can directly impact ocean deoxygenation policies. Focusing on state lawmakers and policy makers is achievable in the short term and may pave the way for future strategies that reach broader audiences and higher levels of government. Directing a call to action to the environmentally conscious State of California is more apt to garner attention and result in a favorable response than tackling the federal government at the outset. I hope that my recommendations for the State of California will provide a good case study on how to conduct ocean deoxygenation communications at a local level for further development of recommendations on a federal level. Communication recommendations at the federal level might need to broaden in scope and consider how ocean deoxygenation could impact the national economy, rather than just focusing on impacts to California.

1. Create a narrative

A narrative is a powerful tool that can simplify complex topics and create and an emotional response. Ocean acidification gave rise to a narrative around a crisis that directly impacted an ecosystem service with the Whiskey Creek Oyster Hatchery. I recommend creating a similar narrative for ocean deoxygenation. One story that ocean deoxygenation could tell is the mass die-offs on Dungeness crab that occurred in 2006 off the coast of Oregon (around the same time as the Whiskey Creek Oyster Hatchery crisis). This die-off was covered by local newspapers, but it prompted no action to address ocean deoxygenation, perhaps because it occurred so close in time to the Whiskey Creek Oyster Hatchery incident. The Dungeness crab die-offs were linked to extremely low levels of oxygen, however this oxygen loss was not tied specifically to anthropogenic climate change. Nevertheless, this incident is the perfect example from which to create a narrative, as the Dungeness crab is an essential commercial fishery in California, as mentioned above. A quote from Science Daily about the event states "The most severe low-oxygen ocean conditions ever observed on the West Coast of the United States have turned parts of the seafloor off Oregon into a carpet of dead Dungeness crabs and rotting sea worms, a new survey shows. Virtually all of the fish appear to have fled the area," (Oregon State University, 2006). This incident can be accompanied with other emerging studies that highlight how ocean deoxygenation will impact other species living along the California coast. McClatchie et al. (2010) predicts 55% habitat loss for cowcod rockfish over the next 20 years in the southern California bight due to hypoxia. Hughes et al. (2015) links hypoxic conditions in estuaries with reduced flatfish nursery habitat. Studies also show reduced oxygen impacting embryonic development and statolith size in market squid, an important commercial fishery and forage species in California (Navarro et al., 2016). These are types of studies that can be highlighted to support a precautionary narrative.

Eutrophication-driven hypoxia can also lend itself to a precautionary narrative. Many coastal ecosystems around the country have felt the impacts of eutrophication, including the Chesapeake Bay, the Gulf of Mexico, and coastal regions off of Oregon. The effects that hypoxia has on these areas can be used to further a narrative built around ocean deoxygenation because the impacts seen in these coastal regions are likely to be similar to impacts of ocean deoxygenation in the open ocean.

The best way for a narrative to elicit an emotional response is to give the story a “human face.” When a narrative seeks to influence policy makers, it is most effective to highlight problems with which their constituents are grappling, or about which they have reason to be concerned. In the case of ocean deoxygenation, fishermen, community members, tribal members, and others are directly impacted by its effects. These stakeholders should be interviewed and encouraged to share their personal stories. A compelling overarching narrative can be constructed around these individual stories.

The impacts of ocean acidification were not entirely clear until the mass oyster larvae die-offs in the Pacific Northwest prompted a response. Waiting for ocean deoxygenation to be responsible for such a crisis in California is irresponsible and foolish. More data emerge every day that emphasize the urgency of recognizing and addressing ocean deoxygenation. A precautionary narrative must be constructed to warn about the harmful effects of ocean deoxygenation and the potential crisis that may occur as a result of long-term ocean deoxygenation.

2. Use coastal eutrophication as a jumping-off point

Ocean deoxygenation impacts all areas of the ocean, including coastal regions and embayments. Coastal regions have long been impacted by eutrophication, which is well publicized and even present to a small degree in federal legislation. Ocean deoxygenation communication efforts should use the publicity of coastal eutrophication as a springboard to launch its own communication efforts. Eutrophication can have compounding effects with ocean deoxygenation, and it is important to draw the connection between the two, because even though they are driven by different mechanisms, they are similar in consequence. The term “dead zone” has become synonymous with hypoxia. Dead zones and OMZs are comparable because they are both areas of extremely low oxygen that change the ecosystem and limit what can live there. The similarity between these two concepts should be highlighted and used in communication efforts. However, it is important to clarify that ocean deoxygenation cannot be solved only in the same way that eutrophication might be – mitigating nutrient runoff will not have a large impact in decreasing open ocean deoxygenation. A narrative should build off of dead zones and coastal hypoxia, but not dwell on it – that issue has long been looked at and addressed.

3. Commission a scientific panel or task force to specifically address ocean deoxygenation

Scientific panels and task forces may significantly raise awareness and directly influence legislation, as in the case of ocean acidification. Currently, the only scientific panel or organization that exists for ocean deoxygenation is the Global Ocean Oxygen Network (GO_2NE). This organization is international and made up of representatives from multiple countries with differing interests and areas of expertise pertaining to the study of ocean deoxygenation. Although this organization effectively stimulates international awareness and influences international policy, I would argue that it does not meet the needs for a California response because their efforts are broad reaching and not focused on how ocean deoxygenation impacts ecosystem services felt by communities in California.

Hypoxia was included in discussions of the West Coast Ocean Acidification and Hypoxia Science Panel, but this body's recommendations discount hypoxia and refer to it mainly as a co-stressor associated with OA. The goals of the West Coast Ocean Acidification and Hypoxia Science Panel and the new California-based Ocean Acidification and Hypoxia Task Force have a clear focus on ocean acidification, which was intentional since the inception of the panels. However, when climate change science panels form, they should begin with the intent of considering the impacts of all multi-stressors on equal footing. Ocean deoxygenation poses a threat on its own that is comparable to the threat associated with ocean acidification, ocean warming, sea level rise, and other associated co-stressors.

In order to get the recognition ocean deoxygenation needs as an ocean health threat, I believe ocean deoxygenation should have a panel dedicated to its impacts. This panel needs to be created to address areas that need more research and to consolidate already available information specifically about ocean deoxygenation. This information can be used to highlight its importance in other climate panels and to policy makers. It is unlikely that the California state government will create such a panel without a clear need, but a good precautionary narrative may arouse a sense of urgency and spark interest and response from the government.

A science panel dedicated to ocean deoxygenation along the coast of California can provide scientifically relevant information to the State of California on how ocean deoxygenation will impact the ecosystem and economy. A panel made up of scientists, members of the fishing industry, members of the community, and other interested parties would provide a good representation of the state and its interests and perhaps give the group enough credibility to be taken seriously by policy makers.

4. Generating NGO, non-profit interest, and funder interest

NGO involvement was essential to the success of OA communication. Many large NGOs have the capacity and resources needed to dedicate effort to raising awareness of an issue they deem important, including influencing and communicating with policy makers. The Ocean Conservancy and the Ocean Foundation helped amplify the message of why the creation of the Washington State Blue Ribbon Panel on Ocean Acidification was needed and helped communicate the outcomes of that panel. This strategy should be employed in the effort to communicate ocean deoxygenation. NGOs that may support ocean deoxygenation awareness should be equipped with relevant communication resources and the latest science. Among NGOs with such potential are the International Union for the Conservation of Nature, the Ocean Conservancy, The Nature Conservancy, The Ocean Foundation, the Ocean Science Trust, and others that care about California's oceans. Other marine non-profits, such as the Monterey Bay Aquarium, The Birch Aquarium, and the Aquarium of the Pacific may also be good targets to help support ocean deoxygenation awareness. Philanthropic organizations must also have an interest in ocean deoxygenation to help fund advocacy programs and communication efforts. Organizations like the Waitt Foundation, and the David and Lucile Packard Foundation are California-based grant funding organizations that might have an interest in providing funding for ocean deoxygenation advocacy. Also, the Pew Charitable Trusts has a marine-based foundation that may be a good target to get involved.

5. Messaging bills and legislation

Narratives and scientific panels can all inform drafted policy. Creating message bills about ocean deoxygenation is a direct way to raise the issue in State legislation. Just like message bills for ocean acidification, these bills will require legislators to take a position and learn about the issue. In order to make these bills more effective, organizations should seek to educate and cultivate key policy makers to create ocean deoxygenation experts within the legislative body. Creating these experts will educate peers across the entire legislative body and produce representatives that will speak to the importance of ocean deoxygenation whenever necessary. These experts will be consulted when ocean health bills are introduced and help spread newly found information. They will also be excellent choices to sponsor message bills. Initial message bills for ocean deoxygenation can be similar to those for ocean acidification, establishing a scientific research and monitoring panel for deoxygenation and changing the language to make ocean deoxygenation the vernacular when referencing open ocean climate-related oxygen loss.

6. Information distribution and consolidation

Policy makers are usually not scientists and they do not devote a lot of time to reading lengthy scientific documents to consider the best action. Information about ocean deoxygenation should be made readily available, easy to understand, and easy to distribute to meet the needs of policy makers. Complex topics must be boiled down to the most important information and presented in a way that easy to understand in policy briefs. Abundant resources are available to create such messaging about ocean deoxygenation, including infographics, brochures, and even short films and video clips.

Infographics are used to present information in a visual format. By the nature of their design and purpose, infographics need to convey only the most relevant and important information about a topic to make it succinct, but informative, while not cluttering up the visual formatting. Infographics can also be designed to present very specific information for a very specific audience. The Ocean Conservancy designed multiple infographics about the potential economic impact that ocean acidification can have on the country, including fisheries landing impact and potential job loss impacts. In light of this I have designed two infographics, one for the basic understanding of the main mechanisms behind ocean deoxygenation to help raise awareness

(Figure 3), and one explaining the possible economic impact on four major fisheries in California (Figure 4). The latter is specifically designed for California policy makers because it displays how ocean deoxygenation can impact an ecosystem service important for a policy maker's constituents.

Similar to infographics, brochures present information in an easy to understand and visually pleasing format, and they tend to be compact and transportable. Based on a series of key facts compiled by GO_2NE, I designed a brochure to be distributed at COP 23 that describes ocean deoxygenation and associated facts in a simplified format. The intended audience was policy makers unfamiliar with ocean deoxygenation with the intention of simply informing them that ocean deoxygenation does exist and should be considered a climate change threat. Although this brochure was designed to be handed out at an international policy-focused forum, the messaging is simple enough that it can be effective in raising awareness with any non-scientific audience.

Short films or videos can also be effective messaging tools. A few short videos exist that with a focus on ocean deoxygenation, including one written by Natalya Gallo, a founder of "Ocean Scientists for Informed Policy," (https://www.youtube.com/watch?v=hrHGwFrqIgg) a group of graduate students at Scripps Institution of Oceanography who strive to see good ocean science influence policy decisions ("Ocean Scientists for Informed Policy," 2018). A longer feature film is a good way to create messaging that can reach a wide audience. A documentary should be created about ocean deoxygenation.

Information about ocean deoxygenation should be easily accessible in a webpage format. Currently, a German website has ocean deoxygenation information (www.ocean-oxygen.org). It consolidates most scientific articles or stories pertaining to ocean deoxygenation, but the design is not user-friendly. Information collected here is hard for non-scientists or policy makers who are unfamiliar with deoxygenation science to understand. The non-scientific public, especially policy makers, have need for a well-organized, user-friendly resource that is a repository for such information. The Ocean Scientists for Informed Policy website (www.oceanscientists.org) has begun to address this need. This website is run by a group of graduate and PhD students at Scripps Institution of Oceanography, with a goal "to see good science used to make well-informed policy decisions that affect the oceans." It includes information on many different ocean health topics that are important for policy, including a limited, but popular, section on ocean deoxygenation. The information on this website is written by scientists and science communicators for a policy audience. Given its association with the Scripps Institution of Oceanography, this group has the potential to expand the website to be a hub of relevant deoxygenation information. If this group does not pursue the expansion of their website, then creation of a website like this by another party is critical. A consolidation of ocean deoxygenation information that is accessible by a lay audience may make the learning experience simpler for policy makers and provide a valuable resource for interested policy makers.

7. Educate the public

Policy makers and legislators make decisions based on the needs of their constituents. It is easy to understand how ocean deoxygenation can be discounted among decision makers, especially those that represent inland counties. It begs the question "how does ocean deoxygenation affect me?" The answer to this question isn't entirely obvious as ecosystem services impacted by ocean deoxygenation are still being studied. However, even without a complete picture, it may be possible to arouse public passion on the issue of ocean deoxygenation. If a representative's constituents value ocean deoxygenation as an important issue to be solved, then the representative will also place value on the issue. In this sense, educating the public is paramount as a vector to communicate ocean deoxygenation to policy makers.

Ocean acidification has become a part of the vernacular at aquariums, museums, and other marine education institutions. To educate the public, ocean deoxygenation must follow suit and be taught as an issue of importance to ocean tourists. A good location for an exhibit on ocean deoxygenation is the Birch Aquarium. As the education and outreach facility to communicate scientific research happening at the Scripps Institution of Oceanography, the Birch Aquarium is an excellent resource to use. Past exhibits at the aquarium have featured climate change and ocean acidification.

The increasing presence of social media should also be used to promote ocean deoxygenation awareness. This can be accomplished when popular and far-reaching NGOs see a need to address ocean deoxygenation and promote it on their social media platforms. Infographics, brochures, or films can also be distributed via social media to reach a wider audience and receive more publicity. Social media can be a powerful tool to share deoxygenation information, as it was for the 2018, Breitburg et al. publication (https://www.altmetric.com/details/31264072). It will also be advantageous to work with social media "influencers," users on social media that have established credibility and a large audience, to spread information about deoxygenation. Well-known NGOs, like those mentioned in recommendation 3, have established credibility and loyal followers and can act as influencers with this information.

8. Rebranding ocean deoxygenation

Scientific jargon can be off-putting and confusing to non-scientists. The term "ocean deoxygenation" is a phrase often met with confused expressions or disinterest. This term can also be hard to say, especially if using it many times in a presentation, or reading it many times in a paper. However, ocean deoxygenation has a very clear meaning and mirrors the cadence and syllables of ocean acidification, creating a connect between the two. This is important, but if we are to talk about ocean deoxygenation more casually and more often, a rebranding will be help create a universal understanding of the term and promote its use. I propose that ocean deoxygenation be referred to as "Ocean Deox" in informal, less-scientific, settings. Ocean deox carries the same meaning while shortening the term and making it easier to say. This term is perfect for public use, especially on social media and resources targeted towards the public or policy makers. It will also be easy to make the transition between ocean deoxygenation and ocean deox as the terms are very similar.

Conclusions

Ocean deoxygenation sounds like a complicated problem. It is a new subject of study, and one that may be obtuse to those without a background in ocean biogeochemistry. Despite this, the main mechanisms and drivers, as well as the main consequences, of ocean deoxygenation can be boiled down to a few simplified statements.

1. Warmer water holds less oxygen than cool water.
2. Warmer water restricts the vertical mixing of oxygen throughout the ocean.
3. Warming raises organisms' respiration rates (oxygen demand).
4. Excess nutrients leads to increased oxygen consumption.
5. Ocean deoxygenation will reduce biodiversity.
6. Ocean deoxygenation will hurt California fisheries.
7. Ocean deoxygenation is expected to continue, unless we do something to stop it.

The culprit of these major changes in the oceans is also clear: anthropogenic climate change is warming the oceans. And finally, the warning message behind ocean deoxygenation is also easy to understand: Just like you and me, ocean animals need oxygen to survive.

Ocean deoxygenation lends itself to a precautionary narrative. Following what made ocean acidification communication a successful campaign, we can identify a clear ocean threat associated with ocean deoxygenation and, by conveying this story to the right audience with a clear action or "ask" associated, secure the resources to respond to that threat. The State of California is an appropriate audience to answer this call because of the State's reliance on ocean resources that are threatened by deoxygenation. It would also be in keeping with California's history of supporting environmental legislation.

Policy makers care about issues that impact their state and their constituents. If we can turn ocean deoxygenation into a human issue – one that impacts our livelihoods and well-being, then California policy makers will pay attention. The recommendations listed above are a starting place. As ocean deoxygenation is an emerging issue, a communication effort on this scale has not been considered before, and there is much opportunity for expansion. Good policy is supported by good science. Good science is fueled by public interest. And public interest is captured by a good story.

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Additional figures

Figure 3. An infographic designed for a non-scientific audience. This infographic outlines the main drivers and mechanisms of ocean deoxygenation with the goal of increasing awareness and helping to start a broader conversation about ocean deoxygenation's impacts.

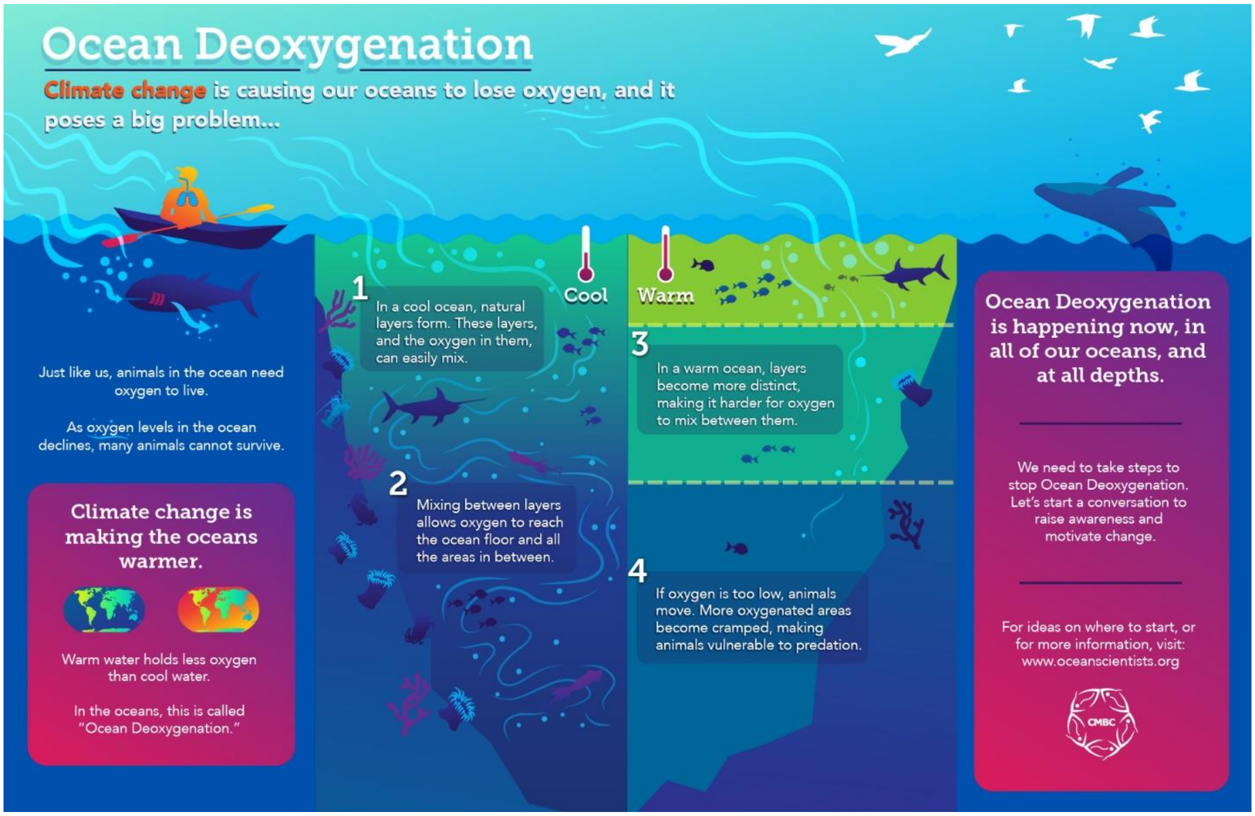

Figure 4. An infographic designed for a policy maker audience. This outlines how ocean deoxygenation can impact some of the most important commercial fisheries in California and is designed to be handed out to legislators in person.