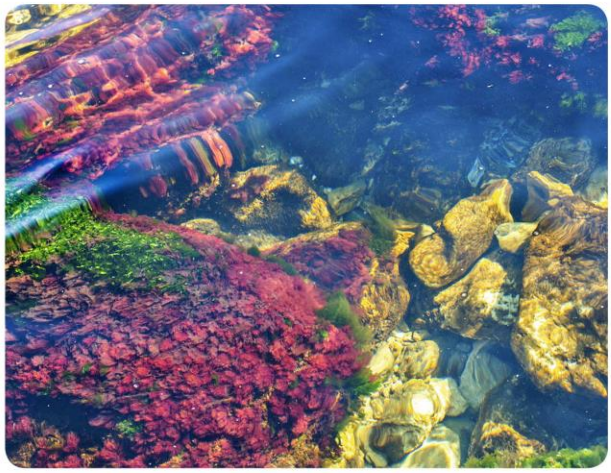
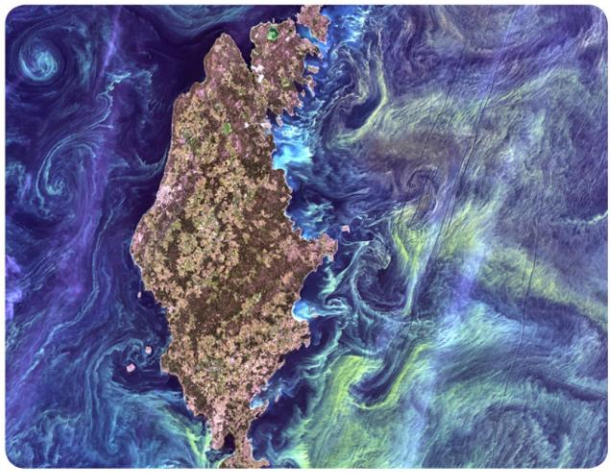
OCEAN ACIDIFICATION

AND ITS PROJECTED IMPACTS ON U.S. ARMY CORPS OF ENGINEERS MISSIONS





BY: PAULA KULLBERG, CARL CERCO, HANNAH CONNERS, AND KATHLEEN WHITE

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This report reviews available information about ocean acidification (OA) in the context of USACE missions and operations and provides a preliminary assessment of OA impacts on the navigation, coastal storm risk reduction, aquatic ecosystem restoration, and Regulatory missions and programs. This report also summarizes knowledge gaps identified in the literature which could be of importance to improving USACE preparedness and resilience to OA.

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Executive Summary

The United States has about 84,000 miles of coastline including the Atlantic, Gulf, and Pacific coasts, the Great Lakes, Alaska, and the islands of Hawaii and the Caribbean. Coastal areas are dynamic environments where land and water meet, continually interact with, influence, and affect one other. The features, characteristics, and inhabitants of coastal environments are very diverse, and yet connected in many ways. An understanding of the ways in which the coast and its inhabitants interact at different spatial scales is crucial for identifying ways to manage and maintain these ecologically and economically vital aquatic resources.

Today, the U.S. Army Corps of Engineers (USACE) faces new challenges to successful performance of its coastal engineering and environmental missions and operations. As the USACE manages the impacts that climate change poses to its vital work in coastal marine environments, it faces a new challenge: ocean acidification (OA). OA is a naturally occurring process that takes place over an extended period of time, in the past usually over thousands of years or longer. It develops when carbon dioxide in the atmosphere is absorbed at the ocean's surface and enters the carbon cycle in the ocean, eventually lowering the ocean's pH and thus increasing its acidity. OA results from natural contributors (e.g., volcanic gas releases, forest fires, and respiration by living organisms) and anthropogenic sources (e.g., burning fossil fuels).

This report represents an initial effort to review available information about OA in the context of USACE missions and operations. Preliminary findings indicate that increasing OA over time could change the behavior and toxicity of some sediment contaminants (particularly heavy metals). OA could negatively impact performance and sustainability of natural features and nature-based coastal flood risk reduction measures involving oyster reefs, coral reefs, and seagrasses. OA will impact marine species in different ways and during different parts of their life cycles, with potential negative impacts to coastal ecosystems that provide ecosystem services and benefits to coastal communities worldwide. Finally, it is possible that in some areas, increasing OA could result in pH levels that are near 6.5, which is the threshold level at which acidified water can negatively impact the Portland cement which binds concrete, as well as calcareous aggregates. This report also summarizes knowledge gaps identified in the literature which could be of importance to improving USACE preparedness and resilience to OA.

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OCEAN ACIDIFICATION

AND ITS PROJECTED IMPACTS ON U.S. ARMY CORPS OF ENGINEERS MISSIONS

Introduction

The United States has an expansive area of coastline—covering about 84,000 miles—including the Atlantic, Gulf, and Pacific coasts, the Great Lakes, Alaska, and the islands of Hawaii and the Caribbean.[1] This wide range of territory spans a variety of geological environments—from rocky coasts, as exist in northern New England and the Pacific Northwest—to the sandy beaches of the mid-Atlantic Coast and areas of the Gulf coast. Other parts of the coast are comprised of large areas of marshes and mudflats, especially in the Mississippi River delta. Coral reef environments characterize still other areas such as the southeast coast of Florida and Hawaii.

Coastal areas are dynamic environments where land and water meet, continually interact with, influence, and affect one other. These features, characteristics, and inhabitants of coastal environments are diverse and, at the same time, highly interconnected. The complexity of interrelationships between the coast and its inhabitants means that an understanding of the ways in which they interact at different scales, from within embayments to regional or even larger areas, is crucial for identifying ways to effectively manage and maintain these ecologically and economically vital aquatic resources.

The U.S. Army Corps of Engineers (USACE) has been involved in the management of our country's coastal resources since the nineteenth century when Congress gave the USACE responsibility for maintaining US waterways and keeping them open and safe for navigation. Over time, USACE missions and operations related to maintenance and stewardship of coastal waterways have expanded. As advances in science and technology have been made, so have USACE methods and tools for carrying out these missions and operations during all phases--planning, design, and implementation. The USACE policies and practices for regulating activities in coastal aquatic environments have also changed as new knowledge, methods and techniques have informed those practices. Today, USACE faces new challenges to successful performance of its coastal engineering and environmental missions and operations. As the nation manages the impacts that climate change poses to vital work in coastal marine environments, it also faces a co-occurring challenge: that of ocean acidification.

Ocean acidification, also referred to as "the other CO_2 problem" (Doney *et al.*, 2009), is a naturally occurring process that takes place over an extended period of time, typically decades or longer (Glossary, IPCC 2014). Natural contributors to ocean acidification include volcanic gas releases, the burning of organic materials (such as forest fires), and respiration by living organisms. This naturally occurring process is being exacerbated and accelerated by the release of fossil fuel emissions, which in turn cause atmospheric carbon dioxide (CO_2) concentrations to rise. Fossil fuel emissions are not the only cause of rising CO_2 concentrations; cement production, deforestation, and other human activities also contribute (Secretariat of the CBD, 2014).

Carbon cycles continuously between the atmosphere and ocean via the ocean's surface. Carbon dioxide in the atmosphere, arising from natural and man-made contributors, is absorbed at the ocean's surface. This CO_2 is eventually transported by a process called downwelling to the deep ocean where additional carbon dioxide is produced through

[1] http://corpscoasts.us/coasts/americascoast.cfm

respiration as organic matter decays (oxidizes). From there, deep ocean currents transport the recycled carbon complexes and, in regions where water is upwelled and warmed at the surface, dissolved CO_2 is re-released to the atmosphere. **Figure 1** presents a simplified illustration of the major carbon dioxide sources in carbon cycling that are involved in ocean acidification. During the carbon cycle in the ocean, a series of chemical reactions occur, lowering the ocean's pH and increasing its acidity, hence the term ocean acidification, or OA for short.

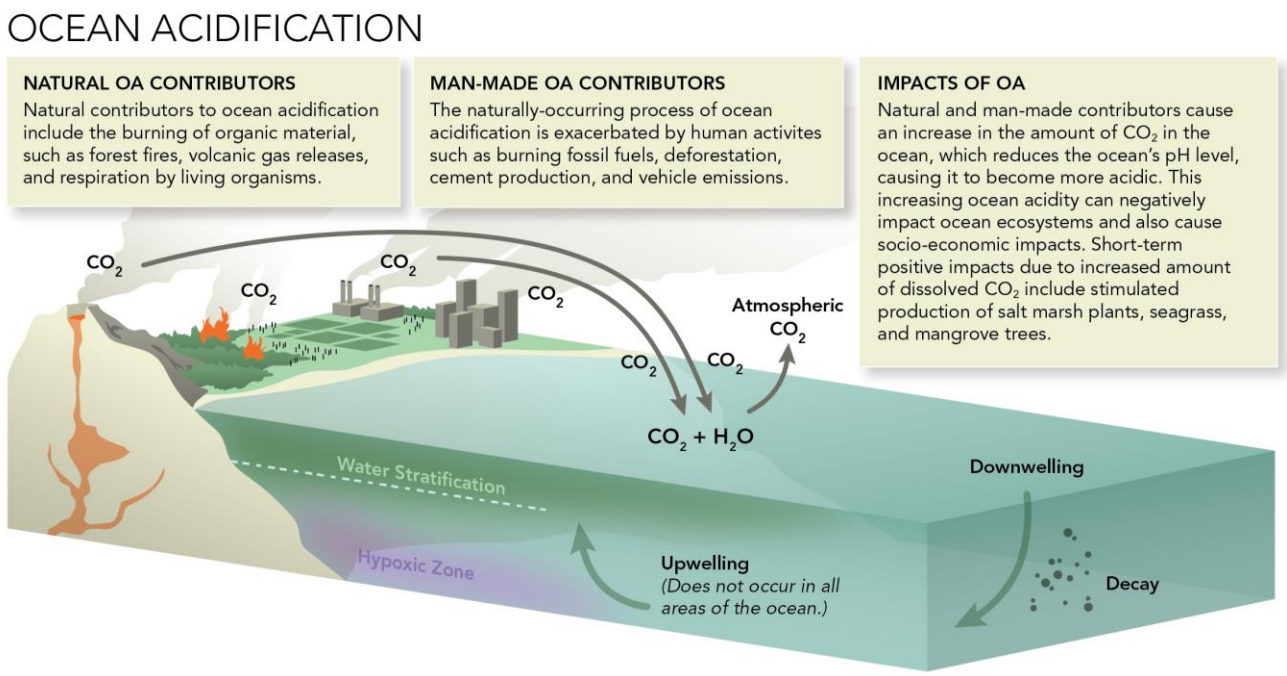

Figure 1. Major carbon dioxide sources that contribute to ocean acidification.

OA changes ocean chemistry in at least three direct ways that have the potential to cause or contribute to severe impacts on marine ecosystems (Logan, 2010):

- **decreased carbonate ion concentration in seawater** (affects calcification)
- **lowered seawater pH** (affects physiology of organisms)
- **increased CO_2 dissolved in seawater** (variably affects growth of plants)

Logan (2010) notes that most of the research that has taken place on ocean acidification has focused on the first of these processes – effects on calcification. Decreased carbonate ion concentration in seawater can negatively impact the calcification process in calcifying organisms (such as corals). Lowered seawater pH can impact the physiological processes of marine organisms, including their acid-base regulation. Increased CO_2 dissolved in seawater can also variably affect the process of photosynthesis by primary producers such as single-celled and multicellular, or macro-algae (Logan, 2010). Other consequences of OA that are of particular interest to USACE missions are also possible, including altered behavior and toxicity of sediment contaminants, changes to performance and sustainability of natural features and nature-based coastal flood risk reduction measures, and potential impacts to concrete in areas with seawater pH below 6.5 (Portland Cement Association, 2015).

The issue today is that the rate of OA is occurring ten times faster than any prior OA occurrence, as recorded in marine sediments and fossils within the last 65 million years (IPCC, 2014). OA is already beginning to show impacts to estuarine and marine organisms and ecosystems in some geographic regions through impacts to fundamental processes such as

nutrient cycling that are both required and mediated by marine life such as corals, shellfish, and other ecologically and economically important marine organisms. These impacts increase risks to ecosystem services including food provision, economic livelihood (e.g., fisheries), cultural values, and tribal traditions. Some marine organisms may adapt and even thrive under conditions of increasing OA (some seagrasses, for example), at least in the near-term. Other organisms, including perhaps half of marine benthic, or bottom-dwelling species (Secretariat of the CBD, 2014), are anticipated to experience reduced growth and survival rates under projected OA conditions.

The ecological stresses due to increasing OA are not occurring in isolation from other environmental changes such as increasing temperature, increased salinity variations, and lowering oxygen levels. While some near-term impacts from OA are now unavoidable, longer-term projected impacts are avoidable to the extent that they depend largely on the amount and rate of increase in atmospheric CO_2 from fossil fuel emissions. The purpose of this report is to review available information about OA, its interaction with co-occurring environmental changes and impacts to estuarine and marine organisms and ecosystems, and to examine current and projected effects of continued OA on USACE missions and operations.

Background

History of Ocean Acidification in the Geologic Record

The geologic record indicates that the current situation is not the first time in Earth's history that OA has occurred. One example of past OA took place during the "Paleocene-Eocene Thermal Maximum," or PETM, which occurred over 55 million years ago (IPCC, 2014). Similar to today, the PETM showed a pattern of warming (Dunkley Jones *et al.*, 2013), ocean acidification (Zachos *et al.*, 2005), and increased runoff and nutrient inputs into coastal shelf ecosystems (Ch. 6, WG2, AR5, IPCC, 2014). The marine fossil record shows increasing atmospheric CO_2 causing warming and increased CO_2 concentrations in the ocean's surface for both past and present climate shifts, while increased runoff and nutrient loading led to enhanced stratification (distinct physical layering) of the upper ocean and a decrease in the dissolved oxygen levels there (Ch. 3, Section 5.3; WGI AR5, IPCC, 2013).

Although the PETM is, in many ways, the clearest historical geological evidence that can serve as an analogy for considering future changes in the ocean, including the rise in ocean acidity that we are observing today, the rate of change in CO_2 levels is different. The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report notes that the "current rate and magnitude of ocean acidification are at least 10 times faster than any event within the last 65 million years" (Ch. 6,WG2 AR5, IPCC, 2014). In order for the geologic record to be directly useful for projecting future impacts of ocean acidification on marine ecosystems, only those events captured in the fossil record that can be unambiguously attributed to OA will be useful (Hönisch *et al.*, 2012). Determining events that can be unambiguously attributed to OA can be difficult, as the fossil record often lacks the resolution needed to enable direct attribution of an observed biological change to a single environmental driver, or to identify various drivers and their relative importance (Ch. 6, WG2 AR5, IPCC, 2014).

The Carbon Cycle

The carbon cycle is one of the major processes involved in the functioning of the Earth's biogeochemical system, including the climate system. The oceans play an important role in that cycle. The oceans are an important net carbon "sink," having absorbed about 25% of the CO_2 released into the atmosphere as a result of anthropogenic (human-caused) fossil fuel emissions since the beginning of the Industrial Revolution in the late 1700s (Ch. 6, WG2 AR5, IPCC, 2014). The effects of this absorption process are twofold: a decrease in the rate of CO_2 buildup in the atmosphere,

delaying the effects of warming, and a measurable impact to ocean chemistry (Logan, 2010). In fact, the IPCC's Fourth Assessment Report (AR4, IPCC, 2012) concluded that it was virtually certain that rising atmospheric CO_2 had changed the ocean's carbonate chemistry (i.e., buffering capacity, carbonate and bicarbonate concentrations). The report went on to say with the same level of confidence, based on calculations of the uptake of anthropogenic CO_2 from the beginning of the Industrial Revolution (from 1750 to 1994), that a 0.1 unit decrease in surface pH has occurred over the global ocean (Sabine *et al.*, 2004; Raven *et al.*, 2005). Measured on a logarithmic scale, this 0.1 unit decrease in surface pH equates to a 30% increase in acidity. Studies show that unless CO_2 emissions are rapidly reduced, there is a high degree of certainty that global mean surface ocean pH could further decrease by about 0.3 units, representing a 170% increase in acidity, by 2100 (Sabine *et al.*, 2004; Feely *et al.*, 2004; Gattuso and Hansson, 2011). The sections that follow discuss the ramifications of this increase in the ocean's acidity on coastal and oceanic processes and ecosystems.

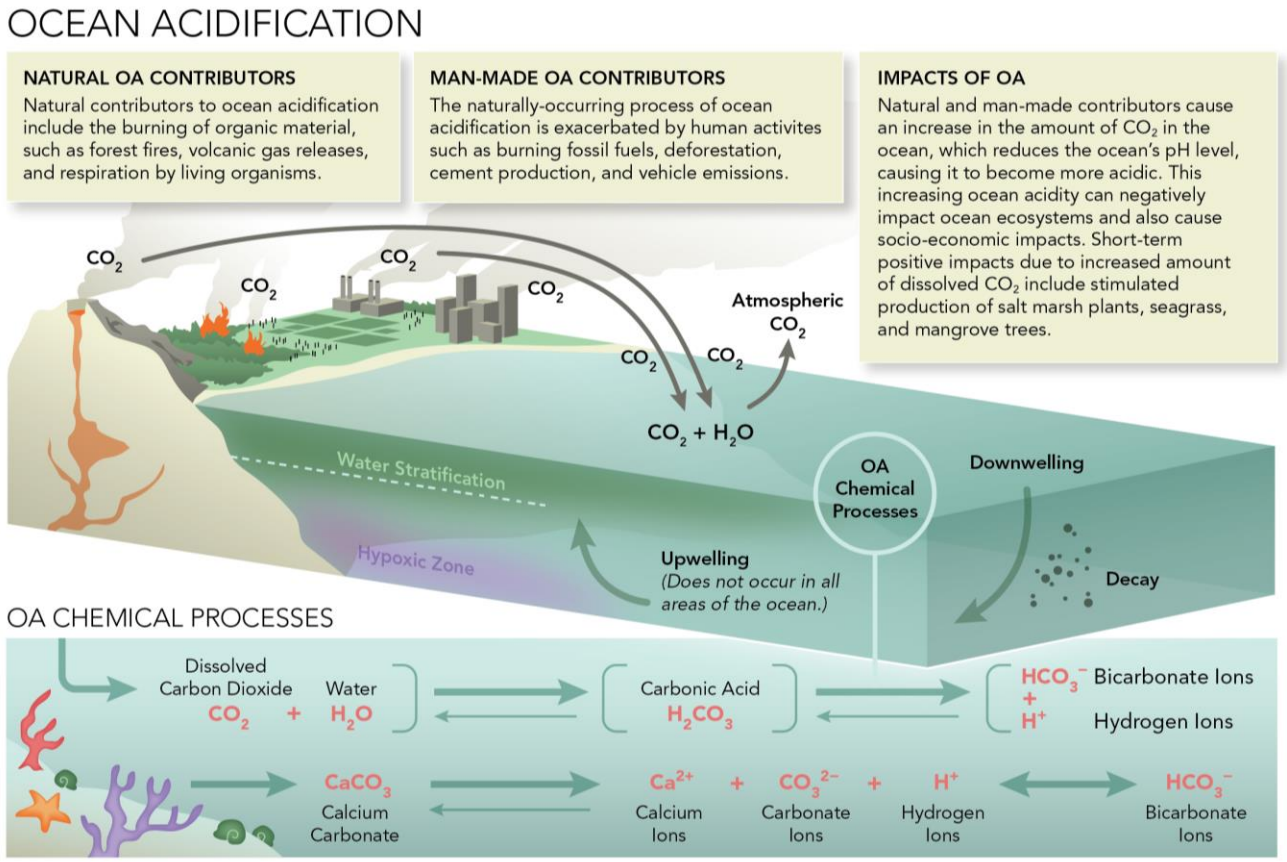

Figure 2. Major processes in carbon cycling that are involved in ocean acidification.

The carbon cycle (depicted in **Figure 2** above) includes both organic and inorganic carbon cycles, both of which affect ocean acidification. The organic carbon cycle, or the cycling of production and decomposition of organic matter, is closely linked to many other elemental cycles, including the marine nitrogen cycle. The inorganic carbon cycle, augmented by the man-made contributors such as fossil fuel emissions listed previously, is primarily responsible for controlling the pH of seawater via a series of chemical reactions referred to as the carbonate system.

The Carbonate System

The carbonate system is an important moderating system in the ocean not only because it controls seawater pH, but because that in turn affects various other chemical states of balance in the ocean. This chemical buffering process begins when inorganic carbon (as CO_2) dissolves in and reacts with water (H_2O). The dissolved inorganic carbon (DIC) then generates carbonic acid (H_2CO_3), which further separates into (and thus increases) bicarbonate ions (HCO_3^-) and hydrogen ions (H^+), and decreases carbonate ions (CO_3^{2-}). The balance of these reactions is strongly dependent upon temperature, pressure, salinity, and the presence of other elemental ions, particularly borate (Wicks and Roberts, 2012). Ocean organisms, or biota, can also affect this equilibrium system, albeit at a local scale over short periods of time (Zeebe and Wolf-Gladrow, 2001). Three other processes that affect the amount of DIC in the ocean are the result of the presence of marine organisms and their physiology: photosynthesis, respiration, and calcification (the production of calcium carbonate shells or skeletons). For example, photosynthesis decreases DIC in seawater, while respiration increases DIC. Calcification removes DIC while producing calcium carbonate ($CaCO_3$), resulting in coral growth and mollusc shell formation. Lastly, the carbonate system is also affected by the ocean's total alkalinity (TA), or the measure of the seawater's acid/base balance. Ocean TA, otherwise known as the ocean's buffering capacity, varies regionally (discussed in detail by Zeebe and Wolf-Gladrow, 2001).

Carbonate Saturation Kinetics & Saturation Horizon

Numerous marine organisms depend on carbonate ions (CO_3^{2-}) for calcification, or the process of making their shells and internal skeletons. This includes various kinds of corals; molluscs such as snails; bivalves such as clams and oysters; sea urchins; tiny plankton such as pteropods, foraminifera, and coccolithophores; and coralline algae. During the calcification process, three mineral forms of calcium carbonate ($CaCO_3$) are commonly produced and secreted (by different organisms): aragonite, high-magnesium calcite, and calcite (Raven *et al.*, 2005). The calcifier type of a marine organism influences its likelihood to be affected by ocean acidification because each mineral type -- aragonite, high-magnesium calcite, and calcite -- behaves differently in seawater depending on various environmental conditions (Logan, 2010). **Table 1** provides some examples of calcifier types and how likely they are to be affected by OA. Carbonate saturation kinetics describes how soluble these three different carbonate minerals in seawater are, in relation to varying temperature, salinity, and pressure. The degree to which seawater is saturated with a carbonate mineral is referred to as the saturation state, denoted by the Greek letter Ω (Logan, 2010). Each carbonate mineral has a different solubility. For example, aragonite is approximately 50% more soluble in seawater than calcite (Doney *et al.*, 2009). In general, the susceptibility of each of the three calcifier types to impacts from OA is illustrated in **Table 1**.

Table 1. Comparison of susceptibility of calcifier types to impacts from OA.

Calcifier Type	Biota Examples	Likelihood to be Affected by OA
Aragonite	Stony corals & shelled pteropods	More
High Magnesium Calcite	Coralline algae & sea urchins	More
Calcite	Foraminifera & Coccolithophores	Less

Marine Carbonate Saturation Kinetics (After Logan, 2010)

The degree to which seawater is saturated with a carbonate mineral (i.e., aragonite, high-magnesium calcite, or calcite) is called its **saturation state**, and it is denoted by the Greek letter Ω. A mineral's saturation state is a measure of its potential to either form or to dissolve in a chemical medium or solvent (in this case, seawater), and it is inversely related to the mineral's solubility. The saturation state of a carbonate mineral in seawater is determined by the concentrations of calcium ions and carbonate ions dissolved in the seawater, in relation to the **solubility coefficient** (indicated by K'_{sp}) for the particular calcium carbonate mineral.

In chemical equation format, this is shown as follows: ($\Omega = [Ca^{2+}]\,[CO_3^{2-}]/K'_{sp}$).

The **solubility coefficient** (a measure of the specific amount of a substance that can be dissolved in a given amount of solvent; here, seawater) varies with temperature, salinity, and pressure. Calcium carbonate solubility rises with decreasing temperature and increasing pressure, and thus increases with ocean depth (colder and denser). Because the saturation state and the solubility coefficient are inversely related for a given ion concentration, the saturation state is highest in shallow, warm tropical waters and lowest in deep and cold, high-latitude waters (Feely *et al.*, 2004).

When the carbonate saturation state in seawater is equal to 1 ($\Omega = 1$), there is an equal chance of either dissolution or formation of calcium carbonate. Thus, at the depth in the water column where there is a carbonate saturation state equal to 1, this location or depth can be considered a chemical "dividing line" or chemical threshold, above which carbonate becomes more saturated in the seawater and below which carbonate becomes more dissolved. This chemical dividing line or threshold defines a two-dimensional surface (i.e., a plane) in the ocean interior called the saturation horizon.

So, when carbonate mineral saturation is greater than 1 ($\Omega > 1$), formation of calcium carbonate is favored; when saturation is less than 1 ($\Omega < 1$), dissolution is favored. The saturation horizon normally occurs at an ocean depth separating shallow, warm surface waters from deeper, cooler water. However, ocean acidification (OA) is causing the decrease of carbonate ion concentrations and therefore decreasing the saturation state of calcium carbonate, thus bringing the saturation horizon closer to the surface (Raven *et al.*, 2005). Because of the higher solubility of aragonite and high-magnesium calcite, the saturation horizons for these mineral forms occur at even shallower depths than that of calcite. Saturation horizons also vary in depth between ocean basins; aragonite and calcite saturation horizons occur at shallower water depths in the Indian and Pacific oceans than in the Atlantic Ocean because of their longer deep-water circulation pathways, resulting in greater accumulation of biologically respired CO_2 (Broecker, 2003).

Carbonate saturation kinetics help determine a horizontal chemical threshold in the water column called the saturation horizon, above which calcifying organisms are able to make and retain their shells and skeletons, and below which they cannot adequately produce their shells and their shells will begin to dissolve. Marine carbonate saturation kinetics is described in more detail in the Marine Carbonate Saturation Kinetics inset box above. Typically, the saturation horizon occurs at the threshold between shallow, warmer surface water above and deeper, cooler water below. OA can cause the saturation horizon to be closer to the ocean's surface (Raven *et al.*, 2005).

The location of the saturation horizon is important because as the saturation horizon becomes shallower, it reduces the volume of the ocean that can safely support calcifying species, which in turn serve as food for other species (major fishery species and humans). In fact, the 2014 report of the Secretariat of the Convention on Biological Diversity (CBD) noted that, although the depth of the saturation horizons varies naturally between ocean basins, the saturation horizon is moving closer to the surface worldwide, and will continue this pattern as more anthropogenic CO_2 is absorbed by the ocean. This same report adds that, in some oceanic regions, the changes in the depth of the saturation horizons by the end of this century are projected to be dramatic, moving from >2000 meters (m) to about 100 m depth in the North Atlantic, from about 150 m to the near surface in the North Pacific (Guinotte *et al.*, 2006), and potentially to reach the surface in the Arctic and Southern ocean (Feely *et al.*, 2012).

Co-occurring Stressors – Global Warming and De-Oxygenation

Two other global-scale environmental stressors will interact with OA to affect marine organisms and ecosystems: global warming and de-oxygenation (CBD, 2014). The IPCC Fourth Assessment Report (AR4; IPCC, 2012) concluded that the average temperature of the global ocean has increased to depths of at least 3,000 m and that the oceans have been taking up over 80% of the heat being added to the climate system (based on observations made since 1961). This warming of the oceans reduces the amount of oxygen available for respiration, and increases the frequency of occurrence and duration of hypoxic (low dissolved oxygen) events (Diaz and Rosenberg, 2008; Rabalais *et al.*, 2009). Low oxygen concentrations in shallow coastal marine waters can cause significant feedbacks to other aspects of the global climate system (including greenhouse gas emissions to the atmosphere) and global biogeochemical cycling (Zhang *et al.*, 2013). **Table 2** summarizes global-scale environmental stressors and OA interactions.

Table 2. Effects of OA, ocean warming, and de-oxygenation on marine organisms and ecosystems (from IPCC 2014).

*Stressor	Induced by	Impacts	Direct Effects	Impacts, including climatic feedback
Ocean Acidification	– Increasing CO_2 in atmosphere – Some local contributions (eutrophication, industrial emissions)	– Change in ocean pH and carbonate chemistry – Progressive dissolution of calcium carbonate	– Reduced calcification and growth in many species – Reef erosion – Changes in carbon: nitrogen ratio	– Reduced abundance of calcifying species; other food web changes – Effects on aquaculture and human food supply – Risk of coral extinctions, with habitat loss and increased coastal erosion – Reduced ocean uptake of CO_2 – Potential warming feedback via **DMS and cloud formation
Ocean Warming	– Increasing greenhouse gases in atmosphere	– Temperature increase – Less ocean mixing due to increased stratification – Loss of polar sea ice – More freshwater runoff in polar regions (reducing salinity) – Sea-level rise	– Reduced solubility of CO_2, O_2, and calcium carbonate – Reduced productivity where more stratified; increased productivity in Arctic – Physiological effects on organisms (metabolism, growth, and survival)	– Poleward shift of (mobile) species' ranges – Coral bleaching – Changes in community composition and food webs – Global reduction in marine productivity – Reduced ocean uptake of CO_2 – Reduced carbon export to ocean interior
De-oxygenation	– Warming reduces O_2 solubility – Stratification reduces O_2 supply to ocean interior – Local causes: eutrophication	– Reduced O_2 availability for respiration, especially in productive regions and mid/deep water	– Slower metabolism and growth of zooplankton and fish	– Effects on abundances and distributions – Shift to organisms tolerant to low O_2 (mostly microbial) – Reduced fishery yield – Increased marine production of methane and nitrous oxide (greenhouse gases)

*Stressor	Induced by	Impacts	Direct Effects	Impacts, including climatic feedback
All three together	– Increasing CO_2 and other greenhouse gases	– Combined stress of reduced pH, warming and low dissolved O_2	– Damage to organism physiology and energy balance – Disrupted food webs	– Major changes to ocean physics, chemistry, and biology – Biodiversity loss, with impacts on ecosystem services – Risk of multiple positive feedbacks, increasing rate of future climate change

Abbreviation: DMS, dimethylsulphide
*Note that these stressors may have either positive or negative effects on marine organisms and their interactions; and other environmental parameters may also contribute to these effects at varying regional to global scales (after Secretariat of the CBD, 2014; based on Turley *et al.*, 2013, also see Bijma *et al.*, 2013).

Interaction with Other Element Cycles – Nitrogen

Like the carbon cycle, the marine nitrogen (N) cycle is influenced by transfers between the ocean and atmosphere. Within the ocean, transformations between organic and inorganic nitrogen are driven by microbes. The predominant form of nitrogen in the ocean is di-nitrogen gas (N_2) which is transformed by nitrogen-fixing bacteria into other forms or complexes that can also be used by other microbes and organisms. The fixed N is then used by organisms and transformed again into other N complexes. The N cycle involves many organisms and transformations that will not be detailed in this review. What is important to note here is that the marine N cycle is closely linked to the carbon cycle and it has a particularly strong effect in shallow coastal areas. As will be discussed further in this report, OA may impact the microbially-driven cycling of N in marine sediments (Laverock *et al.*, 2013). This may affect other chemical and toxicological characteristics of marine sediments and; therefore, may complicate evaluations of suitability of marine sediments for dredging, and also for their open water disposal.

Variability of Ocean Acidification in Coastal Regions (Temporal and Regional Scales)

Coastal areas and ecosystems show greater variability than the open ocean as a result of physical, geochemical, and land-based influences such as freshwater inputs from rivers and biological processes (because more marine organisms live in shallow coastal seas). These additional natural as well as human influences cause coastal seawater pH to be much more variable than the open ocean over space and time (Duarte *et al.*, 2013). This variable acidity has a significant influence on water column chemistry, as described earlier, and also on the marine organisms that live in these dynamic coastal environments. As a result, less scientific consensus exists about the effect of increased acidification in coastal areas than in the open ocean (Gattuso *et al.*, 2013). Human contributors to enhanced seawater acidity in coastal regions can be categorized as either direct or indirect (Strong *et al.*, 2014; see **Table 3**).

The deposition of carbon dioxide, nitrogen oxide, and sulfur oxide from the atmosphere into the ocean all lower the ocean's pH, thereby increasing its acidity (Doney *et al.*, 2007). These direct contributors, also present in noncoastal regions, combine with the indirect contributors (**Table 3**) to variably impact coastal regions. These indirect contributors -- anthropogenic nutrients (e.g., agricultural fertilizers, wastewater, and atmospheric deposition from vehicle tailpipe emissions; Howarth *et al.*, 2012) and rivers carrying freshwater (which impacts salinity) -- end at the coasts where decreased salinity and increased anthropogenic carbon dioxide may (on the West Coast) also combine with coastal upwelling waters. Coastal upwelling, a process where deep ocean currents carry seawater with naturally high CO_2 levels to the surface, can combine with other direct and indirect sources to create local or regional "hotspots" of acidification (Strong *et al.*, 2014). Hotspots in coastal waters of the United States experiencing acidification to varying degrees include Alaska, the Gulf of Maine, Chesapeake Bay, Gulf of Mexico, and the West Coast (Strong *et al.*, 2014).

Table 3. Direct and indirect anthropogenic causes of enhanced coastal acidification (after Strong *et al.*, 2014).

Driver	Direct or Indirect Impact	Process	Effect on pH
Atmospheric CO_2	Direct	Forms carbonic acid, which dissociates, resulting in increased ratio of bicarbonate to carbonate	Decrease
SO_x and NO_x; direct acid deposition	Direct	Deposited as sulfuric acid, dissociates in water; deposited as nitric acid, dissociates to NO^-_3 and H^+	Decrease, dependent on buffering and time frame
Anthropogenic nutrients	Indirect	Runoff as NO_3^- and NH_4^+ from agricultural fertilizers, treatment works, urban areas, deposition from cars stimulates phytoplankton growth and decomposition, particularly in nitrogen-limited estuaries	Decrease in deeper waters with eutrophication
Freshwater delivery	Indirect	Can increase or decrease carbonate ion concentrations. Generally lowers total alkalinity, reducing buffering capacity of coastal water to pH change	Variable, can lower pH
*Upwelling	Indirect	The duration and frequency of upwelling increase of low-pH waters with a high anthropogenic CO_2 content can lower the aragonite saturation state	Decrease

Abbreviations: CO_2, carbon dioxide; SO_x, sulfur oxide; NO_x, nitrogen oxide; NO_3^-, nitrate; H^+, hydrogen ion; NH_4^+, ammonium

*Note that upwelling is listed as an indirect human-sourced contributor to enhanced coastal acidification because upwelled waters have naturally high dissolved CO_2 –low pH–and their duration and frequency are augmented by global warming; upwelled waters also combine with surface waters with human-caused high CO_2 content

Due to the large numbers of marine organisms living in coastal waters, biological processes can also influence the acidity of coastal seawater. For example, some high-quality time series measurements of ocean acidification in coastal ocean areas indicate that the process of ocean acidification can be lessened or enhanced by biological processes taking place, such as primary production (growth by plankton and other sea plants), respiration, and calcification (making of calcium-carbonate shells and skeletons)(Borges and Gypens, 2010; Kleypas, *et al.*, 2011). Some organisms not only have the capacity to affect the chemical and physical conditions of the ecosystem (Gutierrez *et al.*, 2011), but also have the ability to exert some internal metabolic control on seawater pH and variability (Duarte *et al.*, 2013).

Estuaries

Estuaries are specific areas within coastal regions where freshwater and seawater mix as rivers flow into the ocean. In its Fifth Assessment Report, the IPCC (2014) noted that projected changes in riverine discharge and warming may lead to greater thermal and/or salinity stratification (physical layering) of the water column in estuaries and lagoons. Changes in precipitation extremes and concurrent pulses of freshwater to estuaries may cause greater variation and ranges of extremes in salinity levels. Such salinity fluctuations have been associated with adverse effects on biodiversity, benthic macrofauna (larger animals), and ecosystem function (Jeppesen *et al.*, 2007; Levinton *et al.*, 2011; Pollack *et al.*, 2011). These effects are likely to be further complicated by OA. Some research has indicated that eutrophication (an increase in organic matter) can counter OA's effect on the carbonate chemistry of the surface water (Borges and Gypens, 2010), but can worsen OA's effect in bottom water of shallow coastal basins when the organic matter sinks and decays (Howarth *et al.*, 2011; Rabalais et al, 2014).

Seagrasses

Seagrasses are of special importance to coastal ecosystems, and are also culturally and economically important as well. OA is projected to promote the production of seagrasses (as well as other tidal and submerged aquatic plants) due to the increased amount of dissolved CO_2 in the water (Hemminga and Duarte, 2000; Wu *et al.*, 2008; McKee *et al.*, 2012). There is some evidence that increased CO_2 concentrations may have already increased seagrass photosynthetic rates by up to 20% (Hemminga and Duarte, 2000; Hendriks *et al.*, 2010). On the other hand, the co-occurring stressor of ocean warming may counteract this positive effect. IPCC (2014) notes that there is "limited evidence" that elevated CO_2 will increase seagrass survival or resistance to ocean warming (Alexandre *et al.*, 2012; Jordà *et al.*, 2012). Heat waves have been cited for widespread mortality of seagrass species in the Atlantic (Reusch *et al.* 2005).

Shallow-Water Corals

Coral reefs are among the most diverse and productive ecosystems on earth, providing important services to society including tourism, fisheries, and storm surge reduction. They are considered to be a type of "biome", or global-scale system (such as tundras, tropical grasslands, and savannas, etc.) that is distinguished by the collections of ecosystems and species assemblages found there (Mace *et al.*, 2014). Coral reefs, including shallow-water ("warm-water") corals and deep-water ("cold-water") corals, cover less than 1% of the area of the ocean, but may support up to about 25% of marine biodiversity (UNEP-WCMC, 2006). Both shallow-water and deep-water living corals will be impacted by increasing OA. The Secretariat of the CBD (2014) suggests that the long-term survival of deep-water corals seems unlikely because deep-water environments will become inhospitable.

USACE missions and operations generally are located in areas with shallow-water corals, which are made of calcium carbonate secreted by reef-building corals and algae. The ability of coral reefs to survive and grow depends, in part, on the balance between the production and erosion of calcium carbonate and on the success of coral larval settlement (IPCC, 2014). These processes are affected by ocean acidification. Declines in coral cover and calcification have occurred in recent decades, as documented by several researchers (e.g., Gardner *et al.*, 2003; De'ath *et al.*, 2009, 2012; Manzello, 2010). However, globally, the IPCC (2014) notes that the primary climate-related driver of these declines in coral cover and calcification appears to be ocean warming (rather than OA), along with tropical cyclones and changes in freshwater input (Cooper *et al.*, 2012; De'ath *et al.*, 2012). Another negative effect of ocean warming on corals is mass coral bleaching, or the "whitening" or corals due to loss of algae living in symbiosis within the corals. Mass coral bleaching has occurred during events of unusually higher ocean water temperature over the past 30 years, and sometimes mass mortality of corals followed (Kleypas *et al.*, 2008).

Impacts to Organisms, Ecosystems, and Ecosystem Services

OA and other changes in ocean chemistry (e.g., nitrogen cycling discussed earlier) interact together with global warming and de-oxygenation to impact marine organisms. These impacts in turn cause changes to the ecosystems that these animals, plants, and microbes live in, affecting the services the ecosystems provide (see **Figure 3**).

The impacts of OA on marine organism functions and behavior vary and include alterations in: reproduction, photosynthesis by primary producers such as single-celled and multi-cellular algae (Logan, 2010), respiration, calcification, nitrogen fixation and nitrification, and sulfur metabolism. One specific example of the impacts of OA on marine organism functions and behavior is a known interference with brain neurotransmitter function in various resident coral reef fish (Leduc *et al.*, 2013) causing them to lose their fear of predators (Ferrari *et al.*, 2011) and impacting their homing ability (Devine *et al.*, 2011) and possibly their reproductive behavior (Sundin *et al.*, 2012). Wittmann and Pörtner (2013) and Azevedo *et al.* (2015) also discuss sensitivities of various related groups or taxa of marine animals to OA.

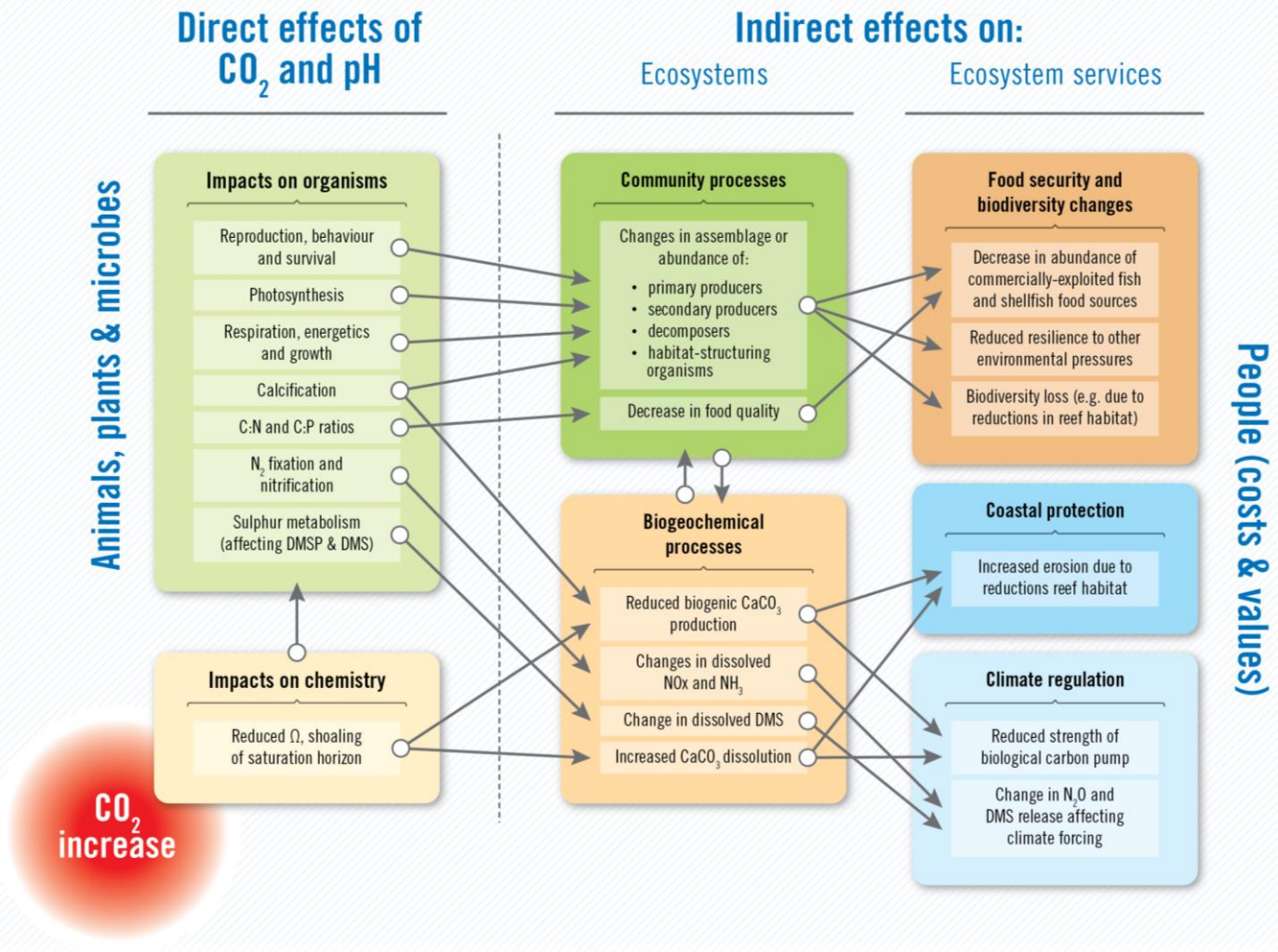

Figure 3. Conceptual view of the impacts of OA on biota, ecosystems, and ecosystem services. (DMSP=dimethylsulphoniopropionate and DMS=dimethylsulphide)(From Secretariat of the CBD, 2014; based on Williamson and Turley, 2012).

Beyond the impacts on individual marine species, it is important to consider potential or anticipated ecosystem impacts as well. Gaylord *et al.* (2015) provides a useful approach that uses ecological concepts to forecast future marine ecosystem impacts from OA. They note that most current research is focused on how individual species experience the direct effects of OA (Gaylord *et al.*, 2015). As a point of comparison, they note that studies of global warming impacts on species show that most temperature-associated cases of severe population decline do not originate from direct physiological responses of species to increased heat but instead from changes to species interactions (Cahill *et al.*, 2013). Furthermore, from studies in the field of ecology (and echoing the paper by Logan, 2010), they suggest the following three key ways or mechanisms by which OA has a strong potential to drive changes in interactions between marine species and their environment (Gaylord *et al.*, 2015):

1. **Higher CO_2 levels in seawater** may boost marine plant growth (primary production) in many species of seagrasses and algae (Cornwall *et al.*, 2012; Harley *et al.*, 2012, Koch *et al.*, 2013). On the other hand, calcifying plants may not fare as well (Kroeker at al., 2010).
2. **Increased OA** (i.e., lower seawater pH) may make it more difficult for marine animals to maintain their internal acid-base balance by costing them more of their energy that they would normally use for other metabolic processes (Pörtner, 2008; Gattuso *et al.*, 1998; Ries, 2011; Comeau *et al.*, 2013; Waldbusser *et al.*, 2013, 2014).
3. **Species interactions** may play a crucial role in marine ecosystem changes.

Gaylord *et al.* (2015) point to several studies that support this third mechanism, suggesting that consequences of OA could occur as a result of modified species interactions (e.g., Fabricius *et al.*, 2011; Falkenberg *et al.*, 2013; Kroeker *et al.*, 2013b; McCormick *et al.*, 2013). Also, there is increasing evidence that long distance interactions (of up to a kilometer) between habitats influence the structure of coastal ecosystems (van de Koppel *et al.*, 2015). An additional paper of interest in this regard is Rocha *et al.* (2015), which analyzed potential marine regime shifts (basically, events in which one set of community inhabitants or species that function and persist together in one way changes over into a different set of community inhabitants that may function very differently together over time). Regime shifts (Folke *et al.*, 2005) can happen to ecosystems quite rapidly in human timescales, potentially causing large disruptions (Möllmann *et al.*, 2015; Conversi *et al.*, 2015). For example, regime shifts could cause the collapse of fisheries, whereby the reconfiguration of marine food webs could have substantial effects on fish yields, the fishing industry, and fishers (Allison *et al.*, 2009; Sumaila *et al.*, 2011). Efforts to attribute perceived pattern changes in ecosystems to an ecological regime shift must be made with caution; however, as variability is typical in natural systems (Doney and Sailley, 2013).

There is a growing literature on the subject of ecosystem services, including by the USACE (Tazik, *et al.*, 2013; Reed *et al.*, 2013). The ecosystem services perspective is increasingly being applied to marine ecosystems in an effort to more fully capture the functional roles and services that marine biota supply to human society. It is especially important to recognize and account for the services that marine ecosystems provide now, particularly in the face of their potential change or loss and subsequent impacts to human well-being.

Moore (2015) notes that, thus far, economic damage estimates from OA impacts on marine ecosystem services have focused mainly on tourism or mollusc fisheries. Coral reefs provide sources of income from tourism, food and fisheries, and protection from storm surge erosion for more than 100 countries in tropical regions of the world (UNEP-WCMC, 2006). The CBD (2014) notes that about 400 million people are dependent upon the ecosystem services provided by tropical coral reefs for their livelihoods. Estimates of economic damages to the US mollusc fishery by the end of the century (about $440 million/year) are on the same order as those that are estimated for increased hurricane damages in the U.S. from climate change by 2099 (Moore, 2015).

One example of a rapid shift in a marine ecosystem took place in the U.S. Pacific Northwest between 2000 and 2008, where both observations and model results captured a dramatic change in the community structure in a rocky intertidal zone (Wootton *et al.*, 2008). What had once been a mussel-dominated community transitioned to an algal-barnacle dominated community in correlation with rapidly declining pH (Wootton and Pfister, 2012). According to the Washington State Blue Ribbon Panel on Ocean Acidification (WSBRPOA, 2012), shelled molluscs are among the most profitable and sustainable fisheries in the nation. The panel also noted that, as of 2012, ocean acidification had already resulted in a loss of almost $100 million, and either directly or indirectly put at risk about 3,200 jobs (WSBRPOA, 2012). **Table 4** identifies studies that have examined projected economic impacts of OA on coastal marine resources.

Increasing OA (in conjunction with other environmental changes such as sea level rise) is likely to have negative impacts on recreation over local and regional scales. For example, a socioeconomic study of coral reefs in southeast Florida noted that during 2000-2001 artificial and natural reefs supported almost 28 million person-days of recreational diving, fishing, and viewing by visitors (Johns *et al.*, 2001). As a result of these recreational and tourism activities, the study noted that local businesses generated about $4.4 billion in sales (almost $2 billion in local income) and over 70,000 full- and part-time jobs. NOAA (2005) reported that reef-related recreation and tourism contributes over $360 million to Hawaii's economy every year and that its nearshore reefs generate almost $1 billion in gross revenue for the state on an annual basis. Thus, states and U.S. Territories that rely on coral reefs (Hawaii, Florida, American Samoa, Guam, and others) for income and jobs related to recreation and tourism may be economically impacted by OA, particularly beyond the next few decades. OA is anticipated, over the longer term, to have mostly negative impacts to aesthetic values of

reefs and other coastal areas, whose historical characteristics become degraded as a consequence of species loss/changes due to OA in combination with other stressors.

Table 4. Summary of studies that examine the economic impacts of ocean acidification on coastal marine resources. (From Secretariat of the CBD (2014), as summarized from Brander *et al.* (2014)).

Study	Impacts	Geographic Scope	Emissions Scenario	Period of Analysis	Welfare Measure*	Annual Value (*U.S. $; billions)
Armstrong *et al.* (2012)	Fisheries	Norway	0.5 pH decrease	2010 – 2110	Revenue Damage Cost	0.01
	Carbon storage	Norway	0.5 pH decrease	2010 - 2110		3
Brander *et al.* (2012)	Coral Reefs	Global	SRES A1B	2000 – 2100	Mixed	1,093
Cheung *et al.* (2011)	Fish and invertebrates	N-E Atlantic	SRES A1B	2005 – 2050	-	-
Cooley & Doney (2009)	Molluscs	United States	IPCC A1F1	2007 – 2060	Revenue	0.07
Cooley *et al.* (2012)	Molluscs	Global	CCSM3	2010 – 2060	-	-
Finnoff (2010)	Fisheries; non-use values	Bering Sea	-	-	-	-
Harrould-Kolleb *et al.* (2009)	Coral reefs; fisheries	Global	SRES A1B	2009 – 2050	-	-
Hilmi *et al.*(2012)	All	Global	-	-	-	-
Kite-Powell (2009)	Coral reefs; fisheries	Global	IS92a	-	-	-
Moore (2011)	Molluscs	United States	RCP8.5; RCP6	2010 – 2100	CV	0.31
Narita *et al.* (2012)	Molluscs	Global	IS92a	2000 2100	CS, PS	139
Rodrigues *et al.* (2013)	Use and non-use values	Mediterranean	-	-	-	-
Sumaila *et al.* (2011)	Capture fisheries	Global	-	-	-	-

Abbreviations: CV, compensating variation; CS, consumer surplus; PS, producer surplus
*Note that impact estimates are standardized to annual values for the terminal year in each analysis (i.e., 2060 for Cooley and Doney and 2100 otherwise) in U.S. $2010 price level

Projected Ocean Acidification Impacts to USACE Missions

Federal Policy

In 2009, Congress passed the Federal Ocean Acidification Research and Monitoring (FOARAM) Act (33 U.S.C. 3701-3708), which mandated the creation of an integrated, multi-agency National Program on Ocean Acidification. Included in the requirements of the FOARAM Act under Section 12405 was a mandate for the formation of an Interagency Working Group on Ocean Acidification (IWGOA). IWGOA was chartered in 2009 and tasked with developing a Strategic Plan for Federal Research and Monitoring of Ocean Acidification (IWGOA, 2014). Though USACE is not represented on the IWGOA, it does have a responsibility to undertake actions, along with its partners, to reduce the adverse impacts of aquatic resource stressors, including OA, under the National Ocean Policy Implementation Plan (NOPIP; National Ocean Council, 2013).

USACE Policy

In response to the release of Executive Order (EO) 13514 in October 2009, the USACE established an overarching policy to mainstream climate change adaptation into all activities. This policy[2], updated in 2014 to reflect EO 13653, states that "Mainstreaming climate change adaptation means that it will be considered at every step in the project life cycle for all USACE projects, both existing and planned… to reduce vulnerabilities and enhance the resilience of our water-resource infrastructure." The policy statement also requires the USACE to begin adaptation now based on the best available and actionable science and to consider the impacts of climate change when planning for the future, so that the USACE can successfully perform its missions, operations, programs, and projects. This report represents an initial effort to review available information about OA, its interaction with co-occurring environmental changes and impacts to estuarine and marine organisms and ecosystems, and to examine current and projected effects of continued OA on USACE missions and operations.

USACE Overview

The USACE has been given responsibility by Congress for a number of major missions and operations. The USACE Civil Works mission is carried out via the following five objectives (USACE-CW Strategic Plan, 2014-2018):

1. **Transform the Civil Works Program to deliver sustainable water resources solutions through Integrated Water Resources Management.**
2. **Improve the safety and resilience of communities and water resources infrastructure.**
3. **Facilitate the transportation of commerce goods on the nation's coastal channels and inland waterways.**
4. **Restore, protect, and manage aquatic ecosystems to benefit the nation.**
5. **Manage the life-cycle of water resources infrastructure systems in order to consistently deliver sustainable services.**

In order to achieve these goals, the Civil Works Program is implemented through nine business areas. These business areas include the three core mission areas of **navigation**, **flood risk management**, and **aquatic ecosystem restoration**; as well as related mission areas such as the Regulatory Program, hydropower, recreation, water supply, and emergency management, for which USACE has been given responsibility. The five objectives of the USACE-Civil Works Strategic Plan incorporate a "systems approach" to water resources management. This approach is important for understanding,

[2] http://www.corpsclimate.us/adaptationpolicy.cfm

projecting, and managing impacts to coastal resources as the USACE, its partners, and stakeholders all work to address the technical and operational challenges related to ocean acidification and other impacts of climate change.

Some of these business areas will be directly or indirectly impacted by OA over the short- and/or long-term. The missions and operations that may already be experiencing effects of OA, or are expected to in the future, include: **navigation**, **coastal storm risk management**, **aquatic ecosystem restoration**, and **Regulatory**. The modes and scales (spatial and temporal) of potential direct and indirect impacts to USACE missions from ocean acidification are discussed below.

Navigation

Keeping America's rivers, harbors, and coastal waterways open for safe navigation to support commerce, including the transport of food, fuel, and other vital goods, is a critically important mission of the USACE. The USACE dredging mission commenced in 1824 when Congress directed the USACE to remove sandbars and snags from major navigable waterways. The USACE must be a good steward of the environment by avoiding or minimizing risk of detrimental effects to the aquatic life that inhabits navigable waterways, including effects of the USACE dredging mission. To avoid or minimize aquatic environmental risks, the USACE (and EPA) must evaluate the potential for such sediments to cause unacceptable impacts to biota if they are dredged, transported, and released or disposed at another site (either open water or upland). USACE employs a suite of EPA-approved laboratory tests that are used, via a tiered approach, to evaluate the suitability of marine sediments planned for dredging for subsequent disposal at upland and open water sites. As discussed below, potential OA impacts may indicate the need for further investigation into altered sediment chemical toxicity and, potentially, revised toxicity tests.

Dredging – Sediment Testing For Disposal Evaluations

Currently, the USACE uses sediment grain size analysis to make suitability determinations for those sediments that are considered likely to be free of contaminants based on their location (i.e., away from any known present or historical point sources of contamination). Grain size analysis indicates the relative amounts of sand, fine silts and clays, and coarser materials (larger granules, coarser pebbles or stones) making up the sediments. This information is important for determining the compatibility of proposed dredged materials for disposal or for beneficial uses such as placement on a receiving beach (in the case of beach nourishment). Grain size distribution also may indicate relative potential for sediments to have contaminants adhered to them; finer silts and clays have a greater affinity (more surface area for their size) for adhesion of contaminants than do sand and coarser sediments. Many harbors and coastal areas of the U.S. have a history of industrial activity, and the USACE requires chemical analyses, and sometimes biological tests, on sediments. Biological testing includes chronic (sublethal) and/or acute (causing death to biota) toxicity tests on various marine organisms in a laboratory to gauge the potential for adverse effects on biota from exposure to sediments that are proposed for open water disposal.

OA is expected to affect the bioavailability of metals within: the water column (Millero *et al.*, 2009), the sediments (Basallote *et al.*, 2012; Roberts *et al.*, 2013; Basallote *et al.*, 2014), and pore water (Ardelan *et al.*, 2009; Roberts *et al.*, 2013; De Orte *et al.*, 2014). Ardelan *et al.* (2009) examined the role of elevated CO_2 in controlling fluxes (exchanges between overlying seawater, sediment, and sediment pore water) of labile (transient chemical species) metals (in particular, aluminum, Al; chromium, Cr; nickel, Ni; lead, Pb; cadmium, Cd; copper, Cu; and zinc, Zn) from contaminated sediments. These studies provide insight into the behavior of the same metals in marine sediments that the USACE and EPA examine in their dredged material testing, but under substantially acidified conditions.

It has been suggested that reduced pH may increase the toxic free-ion concentration of metals such as copper by as much as 115% in coastal waters during the next 100 years (Pascal *et al.*, 2010; Richards *et al.*, 2011). The Cu^{2+} (inorganic form of copper ion) in seawater most often forms complexes with the CO_3^{2-} (carbonate) ion. However, under OA conditions, the Cu^{2+} ion concentration may increase as CO_3^{2-} ion concentrations decrease (Byrne *et al.*, 1988; Roberts *et al.*, 2013). Millero *et al.* (2009) indicated that most divalent metals form strong bonds with organic ligands and fine particulates, and that the stability of these complexes varied between metals. Some investigators have found that the free-ion concentration of other metals, including cadmium, may decrease or show no change (Lacoue-Labarthe *et al.*, 2009, 2011, 2012; Pascal *et al.*, 2010) under projected OA conditions. Roberts *et al.* (2013) observed clear effects of OA on the flux of nickel and zinc, but most other metals they studied exhibited no change.

Metals such as copper and zinc are needed by organisms for various biochemical processes. However, at elevated concentrations they can be toxic, causing DNA damage. Only a few investigations thus far have examined the potential for changes in the bioavailability and/or toxicity of metals under projected near-future conditions for seawater pH as a result of OA (Pascal *et al.*, 2010; Roberts *et al.*, 2013; Lacoue-Labarthe *et al.*, 2009, 2011, 2012; Campbell *et al.*, 2014). Evidence of DNA damage has been used in case studies as a sensitive measure of chronic, sublethal effects of contaminated sediments on the health of marine invertebrates, including amphipods (tiny shrimp-like animals; Neuparth *et al.*, 2005) and polychaetes (marine worms; Lewis and Galloway, 2008), which live within the sediments. Roberts *et al.* (2013) examined the influence of near-future OA on fluxes of labile metals on slightly contaminated and reference sediments in the United Kingdom. They observed a 2.7-fold increase in DNA damage (chronic toxicity) as well as an increase in acute toxicity to benthic (seafloor dwelling) amphipods, but also found that the toxicological interaction between OA and metal contaminants could not be explained by the effects of the lowered pH on the species (chemical forms – such as free ions or metal complexes) of metals alone.

Roberts *et al.* (2013) have proposed that the additive physiological effects of OA and contaminants on the organisms is more important than the changes in metal speciation alone, and suggest that sediment metals testing guidelines may need to be reevaluated to make sure that the tests will provide sufficient environmental protection under near-future OA conditions. Sediment–dwelling species such as amphipods (e.g., *Ampelisca abdita*) and polychaetes (e.g., *Nereis virens*) are routinely used by the USACE and EPA in biological testing on coastal marine sediments, and the results are used in making suitability determinations for open water disposal. Thus, tests of these and similar species conducted under conditions of increased acidification would likely be useful for projecting effects of OA on coastal marine and estuarine organisms.

OA may impact the microbially-driven cycling of nitrogen in marine sediments (Laverock *et al.*, 2013; Krumins *et al.*, 2013). As a consequence, it may be necessary for the USACE to consider the potential additional impacts of OA on N-cycling and resident biota where dredged sediments may be proposed for disposal, if those sediments have levels of metals or other contaminants that may interact with nitrogen cycling in a detrimental manner. Other important considerations relevant to tests and interpretations of impacts to benthic invertebrates under OA conditions (over both short- and long-term; and from organismal to community levels, including with co-occurring environmental stressors), are described in considerable detail in a review by Wicks *et al.* (2012). Hendriks *et al.* (2015) discuss the possible need for studies that more closely mimic the *in situ* conditions to gain a more realistic understanding of OA effects on biota in coastal ecosystems.

OA and Sediment Toxicity – Key Points

Direct effect -- OA is projected to alter the chemical behavior and availability of marine sediment contaminants (especially some metals), and thus toxicity, to biota.

Indirect effect -- OA may cause physiological stress to various life stages of marine organisms, and these stresses may have an additive or synergistic effect on biota beyond that of exposure to sediment contaminants alone.

Future research is needed to examine the influence of OA on sediments, including sediment toxicity. One key area of research that would greatly improve the understanding of the behavior of contaminants (particularly metals) in sediments under OA is the influence of sediment grain size characteristics and organic carbon content on metal fluxes under projected pCO_2 concentrations (Roberts *et al.*, 2013). This information would add to the understanding of metal dissociation mechanisms, as well as improve the ability to predict metals toxicity under OA for a range of sediment types (Roberts *et al.*, 2013).

Dredging - Temporal/Seasonal Work/Dredging Windows

It is unclear at this time whether, and in what way, OA may impact seasonal dredging "windows" (periods of no work) that are established to avoid impacts to the presence, spawning, or migration of fish. It is known that acidification affects how fish and other marine organisms "smell" (their olfactory ability) in their environment in both fresh- and salt-water, and that impaired olfactory-related or -mediated behavior can result in alterations in their foraging, reproduction, and predator-avoidance behaviors (Leduc *et al.*, 2013). Thus, OA could potentially result in dredging operational delays due to greater uncertainty in fish population behavior, and/or greater need for monitoring of or research on fish populations to understand how OA may alter fish behavior.

Coastal Storm Risk Management

The 84,000 miles of U.S. coastline includes a wide variety of coastal features, geologic types, regional sea level changes, and patterns of climate and wave energy. Coastal areas support global trade, provide valuable fisheries and recreation, and add other economic benefits both near the coast and inland through supply chains. Coastal areas are vulnerable to waves, surges, changing sea levels, and coastal storms that can affect public health and safety, damage property and infrastructure, and adversely impact ecosystems and their services. USACE (2013) reports that coastal flood risk reduction can be achieved through a variety of approaches, including natural or nature-based features (e.g., wetlands and dunes), nonstructural interventions (e.g., policies, building codes and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls and breakwaters).

Natural or Nature-Based Coastal Storm Surge Risk Reduction

Following Hurricane Sandy, a concerted effort has been made to increase the use of natural and nature-based features for coastal flood risk reduction (USACE, 2015). Coastal marine ecosystems can provide natural storm surge flood risk reduction (USACE 2013, 2015). For example, both field observations and modeling studies show that coral reefs act as natural buffers to the impacts of tsunamis (Fernando *et al.*, 2005; Gravelle and Mimura, 2008). Ferrario *et al.* (2014) conducted a literature review of the effectiveness of coral reefs in reducing coastal hazards and found that wave attenuation by coral reefs can be similar to or greater than structural measures (e.g., low-crested breakwaters). They also point out the need for further research. Ocean acidification may negatively impact the natural storm surge risk reduction afforded by oyster beds and coral reefs. Living, growing reefs physically attenuate waves and storm surges; however, if these calcifying reef organisms are unable to fertilize, grow, or survive under acidifying conditions (along

with co-occurring stressors: warmer temperatures, less dissolved oxygen), then they will die off, slowly dissolve, and be broken apart by wave impacts. Similarly, studies show that mussels form weaker attachments to the substrate (e.g., sand, cobble, or rock) in the presence of OA (O'Donnell *et al.*, 2013).

In the short-term, OA may lead to increased growth of rooted seagrasses or submerged aquatic vegetation (SAV) in coastal marine and estuarine environments. The rooted vegetation helps bind the sediments and buffer the effects of wave scour. Over the long-term, however, warming due to increased CO_2 is projected to negatively affect survival and reproduction of seagrasses, which would undermine the natural wave buffering in these environments. These effects will be compounded by changing sea levels.

USACE and other stakeholders may be able to rely on existing natural features and constructed nature-based measures to achieve storm surge reduction over the short term. However, over the longer term (i.e., a couple of decades or longer), the combination of changing sea level, ocean warming, and OA could potentially degrade the performance of, or cause the loss of, nature-based storm surge risk reduction measures. This is especially likely for those natural features or constructed nature-based measures which are unable to maintain their areal coverage (e.g., salt marshes unable to migrate inland) or which can no longer adjust to the physiological stresses (e.g., coral and oyster reefs).

Potential for OA to Damage Concrete Structures

Natural waters with low pH can become "aggressive" towards concrete structures. Guidelines (e.g., Portland Cement Association, 2015) indicate that a pH of about 6.5 is the threshold for damaging effects. When pH falls below 6.5, acidified water attacks and begins to dissolve the Portland cement which binds concrete. Acidified water can adversely affect calcareous aggregates as well. Damage to concrete structures from dissolved CO_2 has been reported even before the current acidification trends (Mather, 1964). The Portland Cement Association (2015) cautions that, "Even waters with a pH greater than 6.5 may be aggressive if they contain bicarbonates. Any water that contains bicarbonate ion also contains free carbon dioxide, which can dissolve calcium carbonate unless saturation already exists."

U.S. coastal waters are generally not projected to experience increased OA to the extent that seawater pH changes would be damaging to concrete structures. However, there may be local or regional areas where pH may fall as low as 6.5 due to upwelling, such as in some parts of the Pacific Northwest (**Figure 4**). In such cases, projected acidification of these waters could become deleterious to concrete. Monitoring of local seawater pH conditions and regular examination of structures for accelerated deterioration is advised.

Aquatic Ecosystem Restoration

USACE Civil Works aquatic ecosystem restoration activities seek to prevent, mitigate for, and work to restore damaged or lost aquatic resources via stewardship of public lands and coastal resources. As discussed previously, OA may have a negative impact on the ability of some marine invertebrates to survive, grow, and reproduce; impacting different species in different ways and during different parts of their life cycles. As mentioned earlier, studies already indicate that important ecological and commercial species of bivalves (oysters, mussels) have been negatively impacted by OA, particularly in the Pacific Northwest. Some U.S. coastal areas, such as the West Coast, may be more impacted than others due to upwelling and circulation patterns that periodically expose marine species living there to even greater water column acidities than in other coastal areas that do not experience upwelling. The effects of OA on a variety of marine species, populations, communities, and ecosystems could vary over a range of timeframes. This variability is a consequence of regional and local differences and biotic (individuals, species, interactions between species) responses. Continued increases to the rate and magnitude of CO_2 emissions will have a direct effect on the future rate and magnitude of increase in OA. As experts note (Secretariat of the CBD, 2014), it is not just the absolute value of seawater

pH change that is key to the effects of OA on marine biodiversity but also the change in potential range and variability that poses risk of extinction for many marine species. The marine fossil record indicates that a timescale of many thousands of years may be required for the oceans to "adjust" (equilibrate) or recover to previous lower levels of atmospheric and oceanic (dissolved) CO_2 (Zachos *et al.*, 2005). Thus, even if CO_2 emissions are significantly curtailed, OA will continue to affect the marine environment for the foreseeable future.

Projected effects of OA will vary regionally (**Figure 4**) and are likely to cross many boundaries: coastal USACE (district and division), state, and international (Canada, Mexico). These effects could possibly impact Marine Protected Areas (MPAs), and could require multi-scale stakeholder coordination to understand, prepare for, and manage aquatic environmental impacts. Under the NOPIP, the USACE and its agency partners such as NOAA may share or co-develop a vetted baseline dataset of regional and local coastal marine ecosystem structure, function, species, and physical and chemical characteristics, from which to measure future changes and impacts.

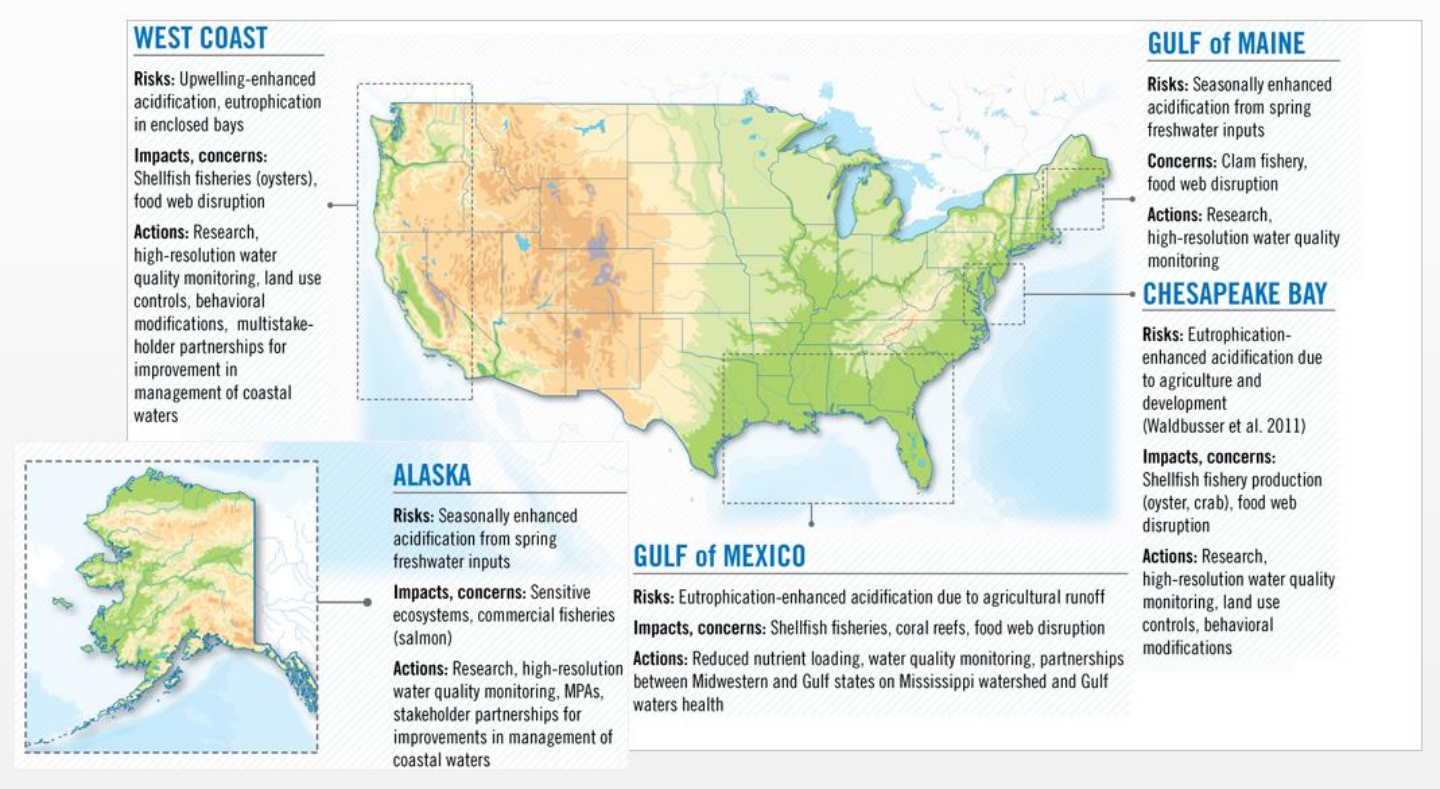

Figure 4. Seasonal and regional drivers of pH change and OA risks vary in different areas of the U.S. coast, and related impacts in these areas will differ as well. This figure shows geographic variations in the sources of risk and impacts of OA as described in recent peer-reviewed scientific studies (after Strong *et al.*, 2014). (Note: Original study did not include Hawaii).

Ocean Acidification Vulnerability Assessments

Recently, a few very informative vulnerability assessments (VAs) have been conducted that clarify ecological, social, and economic risks related to OA in the U.S. In the first local-level, nationwide VA for ocean acidification related to economically important shellfisheries (Ekstrom *et al.*, 2015), the authors applied a well-established VA framework — exposure, sensitivity and adaptive capacity— to assess risks to shelled mollusc harvests. They assessed the spatial distribution of vulnerable people and places in relation to OA impacts on shellfisheries, and developed bioregional maps (based on existing National Estuary Research Reserve System, or NERRS bioregions). These maps provide regional projections showing the anticipated timeframes for reaching coastal OA exposure impact thresholds for bivalve shellfish

(**Figure 5**). Their results showed that 16 out of 23 U.S. bioregions are projected to experience rapidly declining Ω_{Ar} (the saturation state of aragonite), such that detrimental OA sensitivity thresholds for bivalve larvae are met within the next few decades--lowering to Ω_{Ar} of 1.5 by 2050 or they will be exposed to at least one local OA amplifiers. As Figure 5 indicates, Alaska and Washington State are particularly vulnerable to this impact threshold. Another VA study further examines OA risk to Alaska's fishery sector in detail (including commercial and subsistence fisheries – molluscs, crustaceans, and finfish; Mathis *et al.*, 2015). An additional VA for Alaska evaluated the projected OA impacts more specifically to the yields and profits of the red king crab fishery in Bristol Bay (Punt *et al.*, 2014).

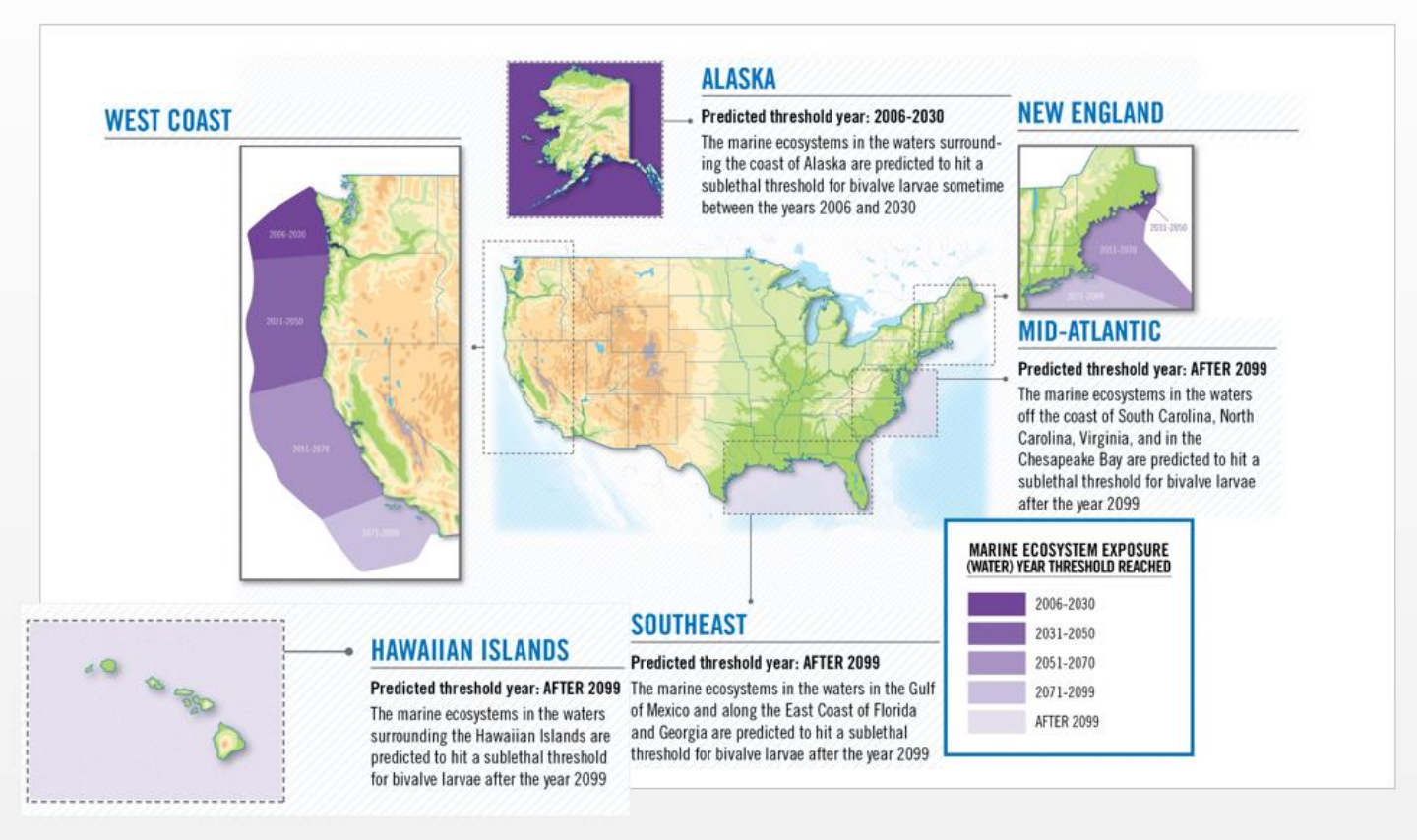

Figure 5. Bioregional maps (based on existing NERRS bioregions) for the U.S. showing regional projections with anticipated timeframes for reaching coastal OA exposure impact thresholds for bivalve shellfish based on climate model projections for representative concentration pathway 8.5. These thresholds could be amplified on the West Coast by strong upwelling of acidified waters; and in parts of the Gulf, Southeast, Mid-Atlantic, and New England coastal regions by two factors: (1) the presence of highly eutrophic estuaries, and (2) river drainage (with low aragonite saturation state and high annual discharge volume). (After Ekstrom *et al.*, 2015).

Ekstrom *et al.* (2015) note that portions of the U.S. Gulf and East Coasts are considered to be in the "medium to highest" ranges of social vulnerability based on projected shellfisheries impacts due to local OA impact amplifiers in those regions. Because USACE has existing large coastal restoration projects in Chesapeake Bay (oyster restoration) and the Gulf Coast (tidal marsh restoration), OA impacts to these regions could impair the long-term success of those restoration projects as early as 2051-2070. Similarly, on the West Coast, the California Bay Delta is identified by Ekstrom *et al.* (2015) as having "medium" social vulnerability due to upwelling-related OA impacts, possibly by 2051-2070. The entire coast of Alaska will encounter and pass the marine ecosystem OA exposure threshold for bivalve shellfish in the near future, perhaps imminently (between 2006 and 2030).

While USACE coastal aquatic restoration projects include many other resources besides bivalve shellfish, the Ekstrom *et al.* (2015) study shows the risks of OA to an important component of many coastal ecosystems, a class of molluscs which can be anticipated to have broader implications for biogeochemical processes, biotic functions, and chemical or nutrient cycling within those ecosystems. Some bivalves (such as oysters and mussels) are also considered "ecosystem engineers" or "keystone species" whose populations can exert large effects on the other aquatic species that live in those ecosystems. VAs can aid in identifying and targeting those monitoring variables and data that are most needed to inform the analysis and to clarify connections between OA, other environmental stressors, and vulnerable communities.

Regulatory Program

The USACE Regulatory Program began as a result of the passage of the Rivers and Harbors Act of 1899, when Congress gave the USACE responsibility under Sections 9 and 10 of the Act to maintain the navigational capacity of navigable waters of the U.S. Under Section 9, the Corps regulates dams or dikes in navigable waters. Under Section 10, the Corps regulates work in, over, or under navigable waters of the U.S., such as dredging or the construction of piers, or that affects the course, location, or condition, of such waters. In 1972, Congress gave the USACE responsibility for administering Section 404 of the Clean Water Act. Under Section 404, the USACE regulates the discharge of dredged or fill material into waters of the U.S., including wetlands. In addition, under Section 103 of the Marine Protection, Research, and Sanctuaries Act (MPRSA, 1972), the Corps regulates the transport of dredged material for the purpose of disposal into ocean waters. The MPRRSA contains the condition that the material may be disposed provided that the Secretary of the Army (via the USACE) determines the disposal "will not unreasonably degrade or endanger human health, welfare, or amenities, or the marine environment, ecological system, or economic potentialities."

Aquatic resources subject to USACE Regulatory Program authorities are anticipated to be affected by OA increasingly over time as coastal and ocean waters become more acidified. Ocean acidification will affect the structure and function of coastal marine ecosystems, including the biogeochemistry and resident biota associated with marine sediments proposed for dredging and open water disposal, as well as these characteristics of the open water disposal sites and reference sites. Thus, the projected OA impacts to sediment testing and disposal issues that were discussed previously also apply to this aspect of the USACE Regulatory mission. As OA increases, toxicity risks to sediment-dwelling biota, from both existing sediment contaminants and changing carbonate chemistry in sediment pore waters, are projected to increase. As more information becomes available, the USACE Regulatory Program will evaluate how to incorporate these new variables into our analysis per the Section 404 and Section 103 requirements and the public interest review.

In addition, since OA has the potential to negatively affect performance and sustainability of natural features and nature-based coastal flood risk reduction measures (e.g. oyster reefs, coral reefs, and seagrasses), there is the potential for an increase in the number of permit applications received for shore protection or bank stabilization activities.

OA could also potentially impact the Regulatory mission when compensatory mitigation is required for unavoidable impacts to aquatic resources as a result of the authorized activity. Mitigation sites located in tidal waters could undergo chemical and biotic changes related to OA as well as to sea level rise or change, with effects varying regionally and over time.

Over the short-term, increases in dissolved CO_2 in seawater may promote increased growth of tidal and submerged aquatic vegetation in coastal mitigation sites and banks, enhancing their resource value. However, over a period of decades, OA and other environmental stressors could negatively impact the capacity of these aquatic resources to retain their intended ecological services. This could occur sooner in areas with OA impact amplifiers (e.g., Ekstrom *et al.*, 2015). In addition, as OA effects on coral reef ecosystems is more studied and understood the USACE Regulatory Program will consider appropriate modifications to cumulative impacts analysis when assessing proposed coral impacts.

Knowledge Gaps

There is an increasing interest and effort to try to project the effects of OA, as well as other climate change-related stressors, on coastal marine ecosystems at local, regional, and global levels. One example of knowledge gaps identified in the literature was presented by Ekstrom *et al.* (2015), in which known regional risks for OA impacts are shown together with suggested areas for research to fill knowledge gaps about projected impacts and their underlying mechanisms (**Figure 6**). This information is needed for vulnerability assessments, which can assist coastal communities to better understand, prepare for, and respond to risks they may face from increasing OA.

Riebesell and Gattuso (2015) noted that the field of OA research involved only a small number of researchers ten years prior, but that the issue of OA has triggered a surge in research in marine sciences, and OA is now among the top three global ocean research priorities (Rudd, 2014). Some 50% of the papers in the field were published in just the preceding three-and-a-half years, and two-thirds of these most recent papers are focused on biological responses and short-term (acclimation as opposed to adaptation) responses of single species or strains in relation to the single stressor variable of OA (Riebesell and Gattuso, 2015). They also noted, however, that it will be the long-term response of marine communities, ecosystems, and the ecosystem services they provide to multiple environmental stressors and drivers that is of most interest and consequence (Riebesell and Gattuso, 2015). One such effort to evaluate and model effects of multiple stressors, including OA, on a temperate coastal ecosystem was carried out by Cornwall and Eddy (2014). They used ecosystem models to examine the independent and cumulative effects of fishing, marine protection, and OA on the structure and function of the marine ecosystem of the Wellington south coast of New Zealand. Such modeling efforts could help inform and improve the USACE's ability to anticipate potential management measures and implement them in advance, if possible, to reduce overall impacts to coastal marine ecosystems.

Boyd *et al.* (2014) identified a key area of research focus needed in order to achieve both improved understanding and better projections of marine ecosystem impacts: that of developing better models for predicting primary producer (especially phytoplankton) responses under regionally-distinct, multi-stressor conditions. The fundamental role of phytoplankton in structuring marine communities and ecosystems makes development of an improved ocean biogeochemistry module that incorporates these complex processes of particular importance to improving these projections (Boyd *et al.*, 2014). To improve the ability to capture changes such as regime shifts in coastal marine ecosystems, it will be crucial to identify and monitor the relevant parameters and indicators ahead of time (Schaeffer *et al.*, 2015; Pace *et al.*, 2015). Only by monitoring a sufficient suite of variables will we be able to discern the patterns and events that can be attributed to OA with or without other stressors (Boyd and Brown, 2015; Gunderson *et al.*, 2016).

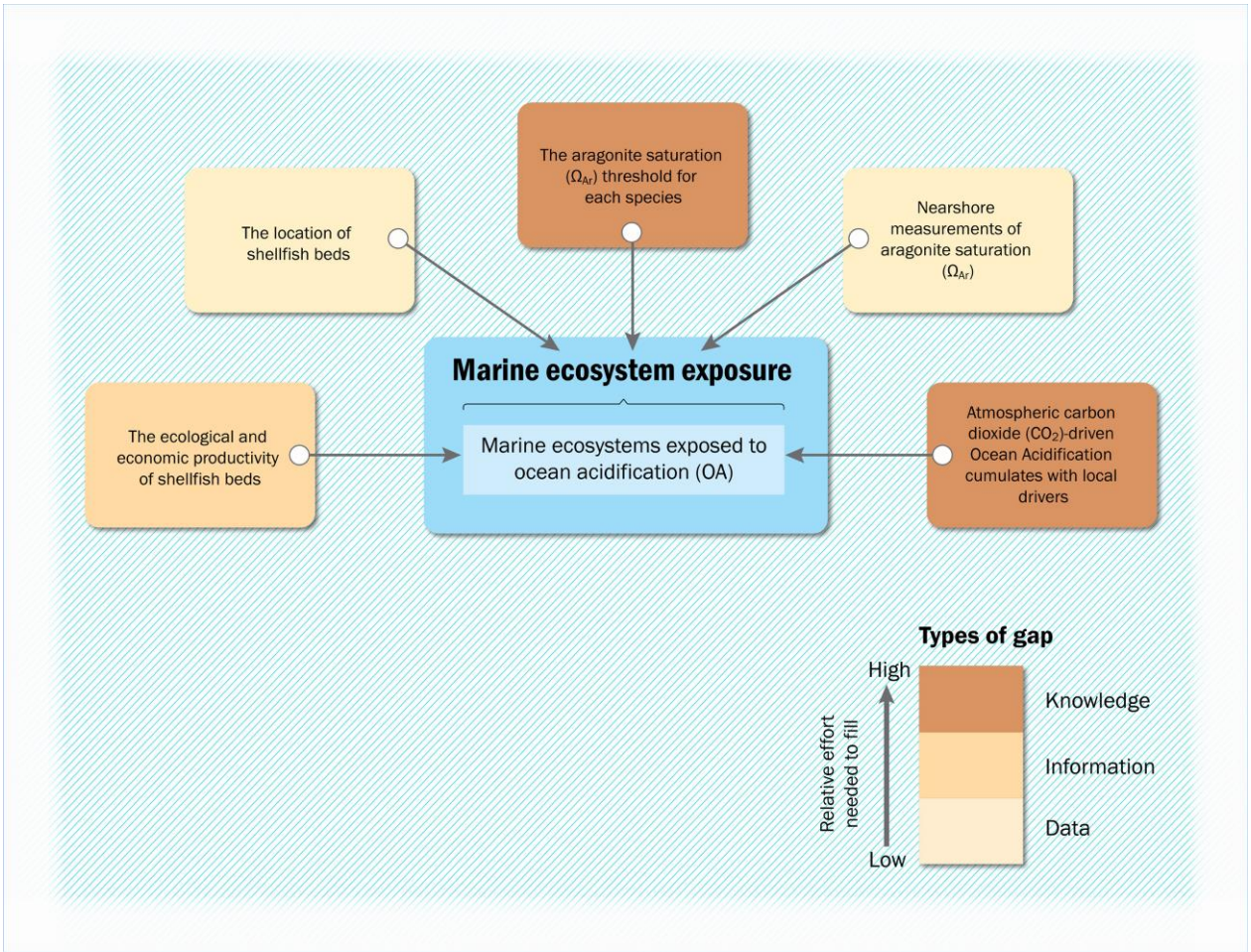

Figure 6. Example of gaps in knowledge of regional risk factors for exposure to OA impacts used in vulnerability assessments (i.e., the mollusc fishery; after Ekstrom *et al.*, 2015.)

Comments on the Future Success of Ocean Acidification Research:

The effects of OA are not just local, regional, or national; they are global in nature. National and international OA programs and initiatives, including the U.S. IWGOA, recognize that progress in the understanding of the way in which changing OA conditions may affect ecosystems and society will depend upon "transdisciplinary science" (TD). TD research merges both natural and social science disciplines to produce solutions to societally-relevant problems (e.g., Yates *et al.*, 2015). OA researchers know that shifts in attitudes and practices will be needed to overcome cultural and institutional barriers so that transformative results can be achieved (Yates *et al.*, 2015). Although TD research projects are more complex to develop and can take longer to see results, such research is likely to be more relevant to solving the problems faced by society in managing the impacts caused by OA.

Conclusions

This report represents an initial effort to review available information about OA, its interaction with co-occurring environmental changes, its impacts to estuarine and marine organisms and ecosystems, and to examine current and projected effects of continued OA on USACE missions and operations. Preliminary findings from this report are that, over time, increasing OA will likely change the behavior and toxicity of some sediment contaminants (particularly heavy metals), and therefore, potentially, affect their suitability for dredging and release at proposed disposal locations. Seasonal variations in these patterns, which could alter fish population behavior and migration, may also affect seasonal dredging windows. These impacts are anticipated to affect the USACE Navigation Program and have the potential to affect Regulatory program evaluations. The information reviewed in this report also suggests that OA could negatively impact performance and sustainability of natural features and nature-based coastal flood risk reduction measures including oyster reefs, coral reefs, and seagrasses. Some U.S. coastal areas (e.g., West Coast) may be impacted more than others as a consequence of upwelling (of more acidified water) and circulation patterns. These impacts could affect the USACE Coastal Storm Risk Reduction mission.

OA is also of concern to long-term stability and maintenance of marine ecosystems because of its impacts on those organisms that rely on calcium carbonate to build their shells and skeletons. OA will impact different species in different ways and during different parts of their life cycles. Studies indicate that important ecological and commercial species of bivalves (oysters, mussels) have already been negatively impacted by OA, particularly in the U.S. Pacific Northwest. These impacts could affect the USACE Aquatic Ecosystem Restoration and commercial aquaculture operations subject to the Regulatory program authorities.

These same processes could negatively impact coastal ecosystems that provide ecosystem services and benefits to coastal communities world-wide, potentially contributing to social and political instability. Finally, it is possible that in areas where there is upwelling and in some Arctic locations (such as coastal areas of the Pacific Northwest and Alaska), increasing OA could result in pH levels that are near 6.5. This is the threshold level at which acidified water can negatively impact the Portland cement which binds concrete, as well as calcareous aggregates.

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