Task Force to Study the Impact of Ocean Acidification on State Waters
Report to the Governor and the Maryland General Assembly

January 9, 2015

Photo by Jay Fleming, MD DNR

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Executive Summary

The *Task Force to Study the Impact of Ocean Acidification on State Waters* was formed by the Maryland General Assembly during its 2014 session through House Bill 118 (http://mgaleg.maryland.gov/2014RS/bills/hb/hb0118e.pdf). The bill states, "The Task Force shall: analyze the best available science regarding ocean acidification and the potential effects of acidification on the ecology of State waters and on State fisheries; and make recommendations regarding potential strategies to mitigate the effects of acidification on State waters and on State fisheries."

Beginning July 2014, the Task Force comprised of representatives from the Maryland Senate, the Maryland House of Delegates, the National Aquarium, the Aquaculture Industry, the Maryland Watermen's Association, the Maryland Departments of Natural Resources (DNR) and the Environment (MDE), the University of Maryland Center for Environmental Science (UMCES), the Chesapeake Bay Foundation, and several outside experts and interested stakeholders met on a monthly basis to evaluate the basic science and problems of acidification in Maryland waters. Much is known about the ocean becoming more acidic from increased introduction of carbon dioxide (CO_2) in the atmosphere, and the importance of upwelling events in the coastal ocean off of Washington State that have impacted the success of shellfish aquaculture facilities. Much less is known about the more complex acidification processes in shallow estuarine environments like Maryland's Chesapeake and Coastal Bays, which are highly sensitive to terrestrial inputs, and the potential impacts that may be posed to the aquaculture industry and important fisheries such as oysters, crabs, striped bass, and other aquatic resources.

The information gaps to understanding the impacts of acidification in Maryland's waters are large. Key findings from Maryland's Task Force focus on seven areas that should be addressed in order to enhance our acidification understanding, its impacts to Maryland aquatic industries, and to leverage resources to capitalize on federal and other state acidification research and monitoring programs.

1.) Maryland needs to enhance monitoring of State waters to quantify scale, patterns, and trends of ocean acidification. It is recognized that Maryland waters and the Chesapeake Bay are some of the most intensively monitored bodies of water in the world. There are significant long-term, and temporally and spatially intensive data sets available to assess nutrient and sediment pollution, the resulting algal blooms and hypoxia, and changes that have occurred due to various management actions and natural conditions. That said, all State waters lack the carbonate monitoring parameters and information to fully assess acidification and the impacts to Maryland's aquatic resources, as the monitoring programs were not designed to quantify acidification. Enhancing existing monitoring networks was identified as a critical need to provide the appropriate data to assess the scale, pattern and trends of ocean acidification to enable planning that could ameliorate or avoid acidification's potential negative effects on our resources.

2.) Establish additional research priorities in estuarine and coastal waters. Much is known about open ocean acidification and atmospheric inputs of carbonates and deep sea upwelling and mixing of carbonate rich waters that contribute to acidification, but the acidification research in estuaries and coastal waters are not well understood, monitored, or studied. Maryland is well suited to expand acidification research because of its proactive legislative initiative to form an Ocean Acidification Task Force, its long-term comprehensive monitoring programs, and its growing aquaculture and fisheries industry. Maryland should take advantage of existing resources and partnerships within the Chesapeake Bay watershed to focus on characterizing the carbonate budget in Maryland State waters and its impacts on ecosystems, with particular focus on key commercially- and ecologically-important species.

3.) Improve coordination with other states and federal resource managers. Other states (Washington and Maine) and the National Oceanic and Atmospheric Administration (NOAA) have recognized that acidification is an emerging issue that needs more research, monitoring and strategies to mitigate the impacts from increased CO_2 in the atmosphere. It is therefore critical to coordinate research, monitoring, and mitigation programs throughout state and regional waters. Cooperative efforts and funding opportunities should be pursued with the Environmental Protection Agency (EPA) Chesapeake Bay Program, the NOAA Ocean Acidification Program, the NOAA Chesapeake Bay Program Office, and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) to enhance our understanding of impacts to Maryland's aquaculture and fishing industries. Maryland's leadership and commitment to understanding acidification impacts to Maryland waters along with the legislative initiative to form the Task Force to Study the Impacts of Ocean Acidification on State Waters will enhance federal funding opportunities. Maryland should also take advantage of existing Chesapeake Bay restoration strategies that help offset the impacts of nutrient enrichment, acidification, and CO_2 emissions such as implementation of nutrient reduction strategies associated with the Chesapeake Bay TMDL; and Maryland's existing greenhouse gas reduction initiatives for a comprehensive CO_2 emissions reduction strategy.

4.) Focus on impacts to key species and associated activities. Acidifying conditions create particular concerns for some of Maryland's high value species such as oysters, blue crabs, striped bass, and other forage fish. Maryland needs to better understand those implications to help mitigate loss or improve performance in key industry or conservation efforts.

5.) Provide direct support to affected industries. Maryland businesses are investing heavily in increased aquaculture production. This business activity is dependent on healthy waters that continue to support oyster reproduction and growth. Additionally, while current hatchery activity is centralized around public hatchery production, private hatcheries are expected to play an increasing role in commercial production support as the industry matures. The Task Force recommends development of a cooperative system to support industry engagement in healthy and growing shellfish production; educate growers about and incorporate relevant mitigation strategies identified by the Washington

State Blue Ribbon Panel on Ocean Acidification (http://www.ecy.wa.gov/water/marine/oa/2012panel.html); support a voluntary monitoring system of key carbonate chemistry parameters; maintain a database of key acidification monitoring and research findings; and encourage regular information exchanges between science, management, and industry.

6.) Pursue legislative action. Maryland DNR should establish an interagency commission or workgroup with representation from industry, state agencies (DNR and MDE), academic and research institutions (e.g., UMCES, Smithsonian Environmental Research Center, and others), the Maryland Waterman's Association, the Chesapeake Bay Foundation, the Oyster Recovery Partnership, EPA Chesapeake Bay Program, and NOAA to implement recommendations, help identify additional resources, and report on the progress of interstate initiatives. Funding should be secured for research priorities, enhanced monitoring, and coordination of activities with affected industries.

7.) Improve communications and outreach. Finally, the Task Force recognized the importance of communication in helping to target policy, management, and industry groups' understanding of the science; the unique challenges in an estuarine environment like the Chesapeake Bay; and the risks to the ecosystem and economy. Therefore, Maryland should develop a targeted outreach plan with an associated website that provides information to watermen and coastal communities to encourage them to become engaged in planning and priority setting for responses to ocean acidification.

Addressing the above seven issue areas identified by the Task Force will position Maryland in both the short- and long-term to leverage existing monitoring, research, and programmatic assets; collect the information necessary to assess the impacts of acidification on our aquatic resources; communicate the results to various stakeholders to meet the demands of our expanding aquatic industries; and mitigate the impacts of rising CO_2 emissions.

Introduction

The *Task Force to Study the Impact of Ocean Acidification on State Waters* was formed by the Maryland General Assembly during its 2014 session through House Bill 118 (http://mgaleg.maryland.gov/2014RS/bills/hb/hb0118e.pdf). The bill states, "The Task Force shall: …analyze the best available science regarding ocean acidification and the potential effects of acidification on the ecology of State waters and on State fisheries; and make recommendations regarding potential strategies to mitigate the effects of acidification on State waters and on State fisheries." Furthermore, "On or before January 1, 2015, the Task Force shall report its findings and recommendations to the Governor and the General Assembly."

Members of the task force are:

Task Force Member	Representation
Bill Ferguson	Maryland Senate
Eric Luedtke	Maryland House of Delegates
Eric Schwaab, Chair	National Aquarium
Tal Petty	Aquaculture Industry
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The Basic Science and Problem of Acidification

Since the beginning of the industrial revolution, with the burning of fossil fuels and conversion of forests into other land uses, carbon dioxide (CO_2) concentrations have steadily increased in the atmosphere. Atmospheric CO_2 concentrations during this time period have greatly increased beyond levels observed historically over the past 400,000 years (Figure 1 - NOAA). Current atmospheric CO_2 levels, as of November 2014, are approaching 400ppm, nearly 5% greater than the beginning of 2006.

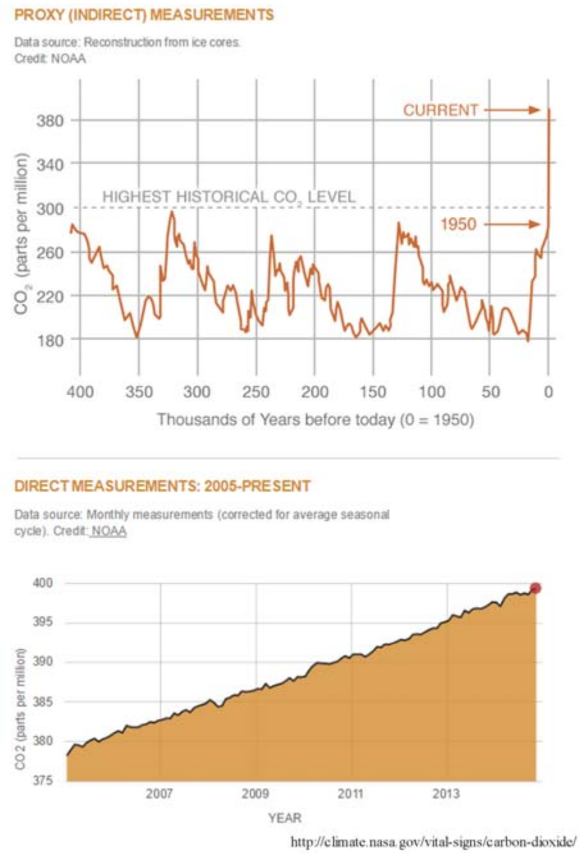

Figure 1. Atmospheric carbon dioxide concentrations during the past 400 million years (top) and during the last five years (bottom).

The concentration of CO_2 in the atmosphere would be even higher had not the ocean absorbed a considerable portion of the CO_2 released. The world's oceans are estimated to absorb 25% of the CO_2 released into the atmosphere annually. This absorption of CO_2 by the ocean has been beneficial in limiting the increase in greenhouse gases in the atmosphere. However, the addition of large volumes of CO_2 into seawater also changes its chemistry, resulting in what is known as **ocean acidification**.

The chemical interaction in seawater is shown in (Figure 2 - University of Maryland, Center for Biological Diversity). Three chemical reactions govern the absorption of CO_2 in seawater. In the first, carbon dioxide combines with water and is converted into carbonic acid. In the second, the carbonic acid breaks down into hydrogen and bicarbonate ions. In the third reaction, the bicarbonate breaks down into carbonate and hydrogen ions. These three reactions are in equilibrium, the balance of which depends upon the CO_2 concentration in the atmosphere.

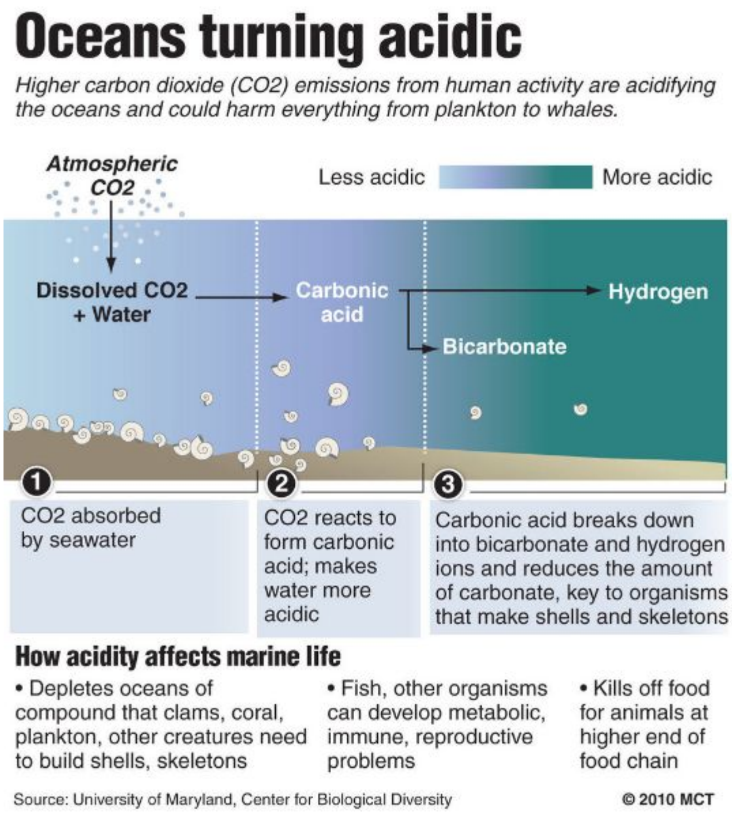

Figure 2. Basic chemistry of ocean acidification.

Increased introduction of CO_2 results in lower pH water (more acidic) and less availability of carbonate ions that organisms combine with calcium to form shells, exoskeletons, and skeletons. Scientists use the term Omega (Ω) when referring to the saturation state of carbonate minerals such as aragonite and calcite. Higher Ω means more availability of carbonate ions for use by organisms. There are critical Ω values. When Ω is >1, calcium carbonate does not readily dissolve, compared to values where Ω is <1 when calcium carbonate, and hence the shells, exoskeletons, and skeletons of animals will dissolve.

The atmospheric contribution of CO_2 has been recognized as the driving component of acidification in the open ocean, a concept that is commonly known as 'Ocean Acidification v1.0'. In this scenario, small changes in pH are significant and occur relatively slowly.

'Ocean Acidification v2.0' is a bit more complex and combines the influences of atmospheric CO_2, with physical oceanographic factors such as upwelling of carbon-rich, lower pH, deep ocean water. Such upwelling events have been, for example, important in the coastal ocean off of Washington State, impacting the success of shellfish aquaculture facilities. Under 'Ocean Acidification v2.0' the overall change of pH is slow. However, abrupt but temporary changes in pH can occur as different water masses move over individual geographic areas, such as occurs when low pH water is upwelled from depth.

The impacts of ‘Ocean Acidification v. 2.0’ can be ameliorated if processes, whether natural or commercial, can be “stopped” during periods when the location is affected by the upwelling.

Things become even more complex in shallow estuarine environments like the Chesapeake and Coastal Bays, and lead to ‘Ocean Acidification v3.0’. Inshore and estuarine waters are lower in salinity, and are naturally less alkaline, having less buffering capacity than seawater against larger swings in pH. In addition, estuaries are productive zones teeming with life and human influences. Nutrients in coastal and estuarine waters, such as nitrogen and phosphorus, enter coastal and estuarine waters in excess through wastewater, storm water, and agricultural runoff which fuel algal blooms that then die-off and are consumed by bacteria. The respiration of these microbes uses up oxygen, often resulting in hypoxia: Waters with dissolved oxygen low enough to reduce growth or survival of aquatic organisms. Physical processes such as thermal or saline stratification in estuaries can compound hypoxia by limiting the exchange of oxygen into deeper bottom waters. But this same respiration also produces CO_2, which dissolves into the water, lowering the pH. Ultimately, the process of respiration is a significant cause of both hypoxia and acidification of coastal waters. One important attribute of ‘Ocean Acidification v3.0’ is that changes in pH can be substantial, rapid, and cyclic.

Data from the Maryland Department of Natural Resources’ (DNR) continuous monitoring program show the significant relationship between stations with lower dissolved oxygen and lower pH, expected if respiration is an important agent in acidification (Figure 3 - www.eyesonthebay.net and Breitburg et al., 2015).

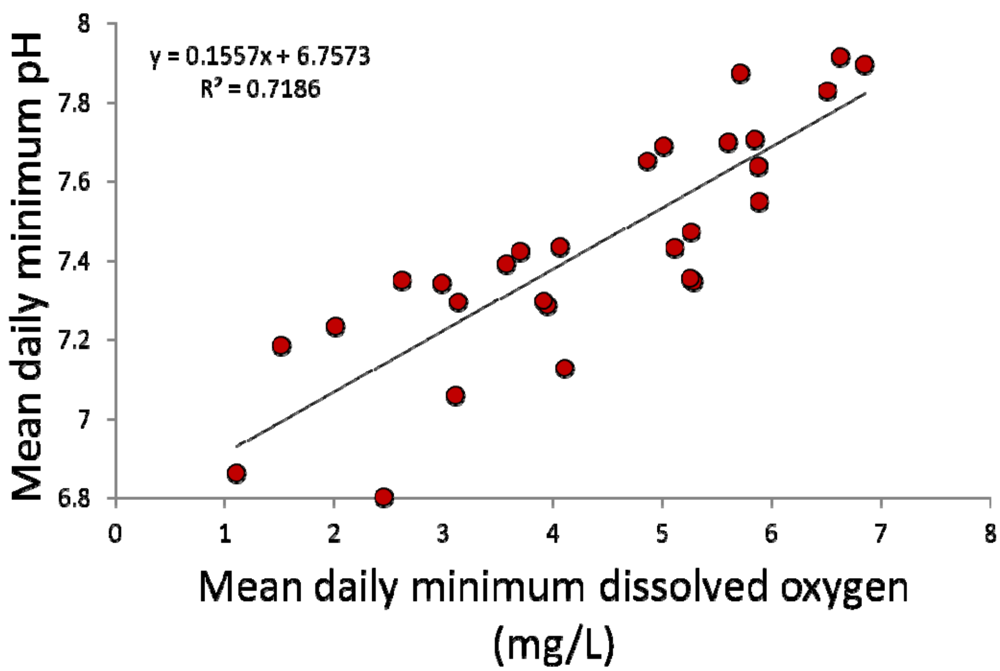

Figure 3. Mean daily minimum pH versus mean daily minimum dissolved oxygen at MD DNR continuous monitoring sites.

The daily cycles of photosynthesis and respiration induce similar cycles in the levels of dissolved oxygen and pH. These cycles of coupled low oxygen and lowered pH often reach their minimums in the early morning. Data from MD DNR's continuous monitoring program (www.eyesonthebay.net) illustrate this phenomenon (Figure 4 - Breitburg et al., 2015). Tidal movement and freshwater flow can also produce significant changes in the pH environment at a given location.

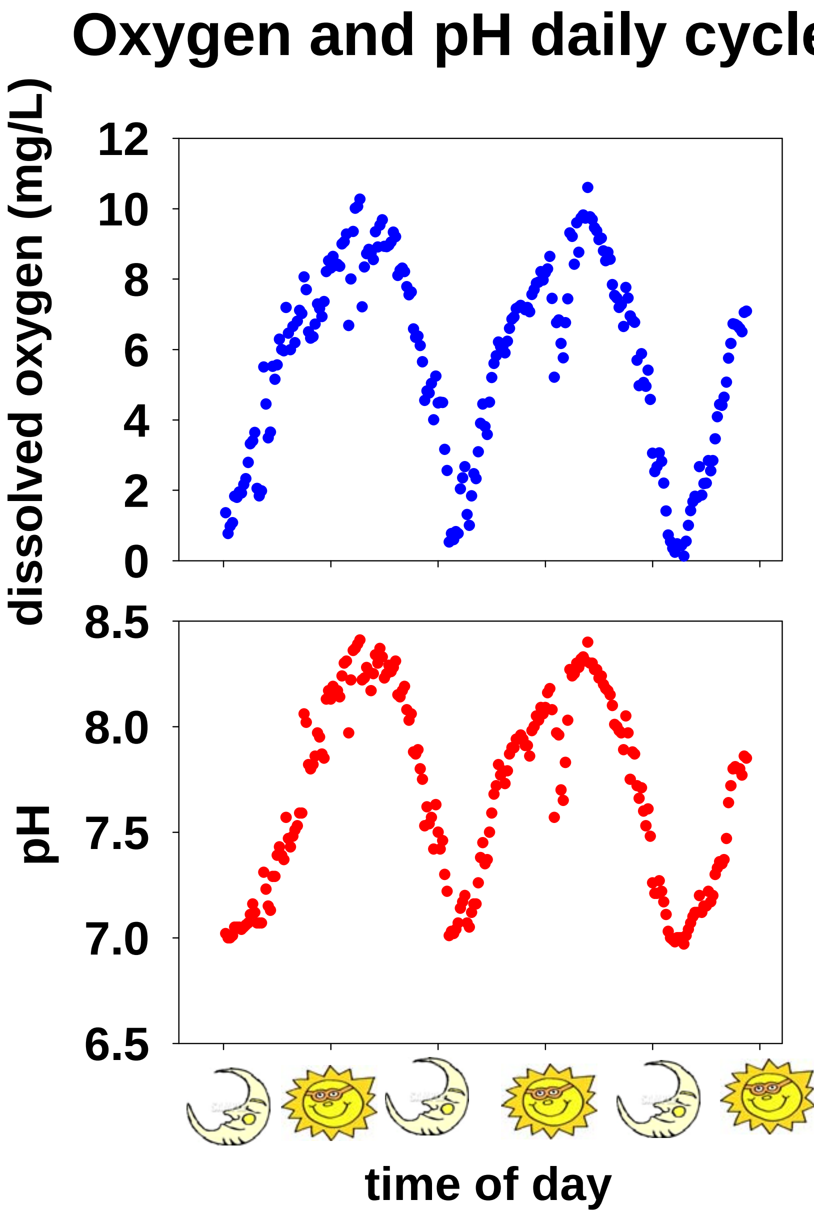

Figure 4. Example of couple dissolved oxygen and pH fluctuations from a MD DNR continuous monitoring site.

In addition to atmospheric and respiratory contributions to acidification, Maryland waters have other factors which can modify acidification and complicate our understanding of processes contributing to the cycling of carbon. We must recognize the physical difference between the coastal ocean and inshore waters, such as the Chesapeake Bay, when comparing the impacts of ocean acidification on these systems. Unlike the ocean environment, the Chesapeake Bay is a shallow estuarine system with extensive shoreline and significant watershed inputs of freshwater and anthropogenic pollution. The role of interactions between land and water, regional geological differences, biogeochemical exchanges between the water column and benthos, and riverine input all contribute to acidification in shallow estuarine systems and need further study (Alliance for Coastal Technologies, 2014).

As noted above, the process of respiration is a significant cause of both hypoxia and acidification. Specific to the challenges of ocean acidification, it is therefore even more important to maintain and continue our efforts to reduce excess nutrients entering all of Maryland's waters. Such efforts not only promote restoration and improvement in oxygen levels to support oysters, crabs, fish, and other aquatic resources; but also explicitly reduce the potential impacts from acidification.

Chesapeake Bay Restoration Strategies Directly Help Address Acidification

Chesapeake Bay Nutrient Reduction Strategies

Efforts to control nutrients are particularly important for the Chesapeake Bay. Maryland and the other Chesapeake Bay watershed jurisdictions comprised of Virginia, Pennsylvania, New York, Delaware, West Virginia, and the District of Columbia along with the Environmental Protection Agency (EPA) and the Chesapeake Bay Commission, collectively form the Chesapeake Bay Program Partnership, which has identified excess nitrogen, phosphorus, and sediments as the major problem facing Chesapeake Bay. Most of the mainstem Chesapeake Bay and its tidal tributary waters are listed as impaired because of excess nutrients and sediment. These pollutants cause algae blooms that consume oxygen and create "dead zones" where fish and shellfish cannot survive, block sunlight needed by underwater Bay grasses, and smother aquatic life on the bottom. As an expression of that commitment, President Obama issued Executive Order 13508 on May 12, 2009, which directed the federal government to lead a renewed effort to restore and protect the Chesapeake Bay and its watershed. The EPA implemented a Chesapeake Bay Total Maximum Daily Load (TMDL) in December 2010 that set nitrogen and phosphorus loads for each Bay watershed jurisdiction to be achieved by the end of 2025. The individual Chesapeake Bay jurisdictions' Watershed Implementation Plans (WIPs) have been established to achieve those nutrient load allocations for each basin.

The process of biological respiration is a significant cause of both hypoxia and acidification. In addition to directly addressing nutrient and sediment pollution, full WIP implementation by all jurisdictions will buffer potential negative impacts from acidification. It is therefore important to maintain and continue our efforts to reduce excess nutrients entering the Chesapeake Bay, from both the watershed and atmosphere, to promote restoration and improvement in oxygen levels to support oysters, crabs, fish, and other aquatic resources and reduce the potential impacts from acidification.

Reduction of Greenhouse Gas Emissions and Response to Climate Change

Greenhouse gases (GHGs) are not like other air pollutants. GHGs are so named because they are heat-retaining gases that are fairly abundant in the atmosphere. Ozone, fine particles, and other air pollutants are found in very small amounts and undergo chemical changes in the atmosphere so that harmful levels typically dissipate after a few hours, days or weeks. GHGs, on the other hand, accumulate in the atmosphere and stay there for a very long time. A pound of carbon dioxide emitted today by driving a car or using electricity generated by burning fossil fuels, such as coal, will still be in the atmosphere decades to centuries from now. It is this persistence in the atmosphere coupled with their heat-retaining properties that create the problem. It does not matter if the GHG is emitted in Maryland or elsewhere around the globe - the climate impact is the same.

In late 2014, the Intergovernmental Panel on Climate Change (IPCC) issued its Fifth Assessment Report, "Climate Change 2014: Impacts, Adaptation and Vulnerability." This report confirms conclusions from earlier IPCC reports and other publications, such as the 2011 National Academy of Sciences' National Research Council report, that the scientific evidence points to human-caused emissions of GHGs as being most likely responsible for the measureable changes in climate and noticeable increases in unusual weather across the world over the past few years. The latest IPCC report (Chapter 6) specifically calls out ocean acidification as an issue of concern.

Climate change resulting from the accumulation of GHGs will affect Maryland in a variety of ways. More obvious impacts could include continued sea-level rise; an increased risk for extreme events such as drought, storms, flooding, and forest fires; more heat-related stress; the spread of existing or new vector-born disease; increased erosion and inundation of low-lying areas along the State's shoreline and coast; and acidification of Maryland's waters. Climate change raises the stakes in managing these problems by changing the frequency, intensity, extent, and magnitude of these problems.

Greenhouse Gas Emissions Reduction Act

As a Maryland legislative initiative adopted as a Maryland law in 2009, the Greenhouse Gas Reduction Act (GGRA) requires the Maryland Department of the Environment (MDE) to work in cooperation with State agencies to develop a 2012 GGRA Plan to achieve a 25% reduction in GHGs by 2020, from a 2006 baseline, that creates jobs and improves the economy. The Maryland GGRA Plan (http://climatechange.maryland.gov/site/assets/files/1392/mde_ggrp_report.pdf), published in October 2013, identifies a suite of cost-effective GHG reduction programs which, if fully implemented, will benefit Maryland consumers, businesses, and the State's economy as a whole. The Regional Economic Studies Institute (RESI) recently estimated that by implementing these policies, Maryland could see as much as a $1.6 billion increase in the State economy by 2020.

Energy efficiency is the fastest and least expensive approach available to reduce GHG emissions. According to the EPA-Depart of Energy (DOE) National Action Plan for Energy Efficiency, energy efficiency will not only help to address GHG emissions, but actions in this area also can lower energy bills, help stabilize energy prices, enhance electric and natural gas system reliability thereby reducing the need for new generation sources, and reduce harmful air pollutants. In fact, some states with well-designed energy efficiency programs are saving enough energy at about half the cost of building a new electric power plant to avoid the need for a new power plant.

Social, Economic and Environmental Impacts of Acidification in Maryland Waters

Maryland is often described as 'America in Miniature' because of its geographic diversity. This diversity carries through to the nature of Maryland's aquatic environments. The full spectrum of marine and estuarine aquatic environments can be found within Maryland, including the open ocean; shallow Coastal Bays with generally high salinity, but directly influenced by both ocean and rivers; and the Chesapeake Bay, one of the world's most productive estuaries. In this regard, Maryland must deal with the impacts from all facets of acidification, ranging from aforementioned versions 1.0 to 3.0.

In general, Maryland must consider the following in planning for ocean, coastal, and Chesapeake Bay acidification:

- In open ocean waters, increases in atmospheric CO_2 concentrations are causing acidification effects similar to those occurring in most of the world's oceans.
- In Maryland's near-shore ocean environments, physical oceanographic processes, such as mixing, may be having additional impact, but as yet are not fully understood.
- In Chesapeake Bay and parts of the Coastal Bays, acidification, eutrophication induced hypoxia, and increased temperatures could have compounding effects on aquatic organisms.
- Acidification may cause a range of impacts to fish and shellfish and their prey. Reduced reproductive success, more susceptibility to predation, reduced growth due to increased energy expenditures, and increased mortality are all potential concerns.
- Fisheries management strategies may need to adapt to changing water chemistry conditions, changing predator and prey abundances and other system perturbations.
- Commercial aquaculture operations in particular may need to be aware of and respond to changing local or regional water quality conditions.
- Other water quality dependent enterprises may also need to be aware of and adjust to changing water quality conditions.

Economic Value of Fisheries and Coastal Resources in Maryland
Maryland's diverse natural resources support a wide variety of commercial and recreational coastal industries. In 2011, Maryland's coast supported more than 2.8 million jobs representing $107.5 billion in wages in coastal industries including living resources, marine construction, ship and boat building, marine transportation, offshore mineral extraction, and tourism and recreation (NOAA, Economics:National Ocean

Watch (ENOW) site: http://coast.noaa.gov/digitalcoast/data/enow). For those industries that may be more likely to experience some of the earliest effects of ocean acidification – namely those that rely on healthy, functional ecosystems, such as living resources related tourism and recreation – this translates to about 44% of the State's estimated Gross Domestic Product (GDP). In a state where such a significant portion of its economy is in some way inextricably linked to coastal resources, ocean acidification and its possible effects on coastal resources and environments must be taken seriously.

In recent years, the State has made efforts to better understand the type of industries, operators, and individuals that rely on the coast, especially in the recreational sector. Over the past two years, Maryland has worked with a variety of local citizens; business owners; non-governmental organizations; local, state and federal agencies; and many others to identify specific recreational sectors that use the State's coastal waters and where these activities are occurring and at what times. Information about more than two dozen recreational uses has been collected and digitally mapped in the Chesapeake Bay and its tributaries (through a pilot program in the Choptank River), the Atlantic Coastal Bays, and the Atlantic Ocean (out to 200 nautical miles). This information has been collected for boating-for-hire uses, recreational fishing and hunting uses, and general recreational uses. Paired with monitoring information and expectations about how ocean acidification might impact Maryland's coasts, this information could be utilized to get a clearer picture of where certain activities and coastal industries reliant upon healthy ecosystems may be affected.

While current industries may be affected by ocean acidification, it should also be recognized that any number of emerging or future industries in and along any of Maryland's coasts may also stand to be affected. Whether it is emerging aquaculture, energy, recreational, or other industries, possible future impacts would vary but could be considerable.

Commercial and Recreational Fisheries

The Chesapeake Bay is one of the most productive bodies of water in the world. It supports a wealth of commercial and recreational fisheries, and has enormous economic contribution to the State. A study by the NOAA National Marine Fisheries Service (http://www.st.nmfs.noaa.gov/Assets/economics/documents/feus/2009/MA_MDTables_Econ.pdf) estimates that the Maryland statewide seafood industry contributed 14,778 jobs, $1.65 billion in sales, $408 million in income, and $635 million in value added impacts to the State's economy in 2009. Recreational fisheries contributed 5,714 jobs, $770 million in sales, $257 million in income, and $392 million in value added impacts to Maryland's economy in 2009. An additional $792 million was spent in 2009 on angler trips and durable expenditures such as tackle, equipment, boat/vehicle expenses, and second homes.

Aquaculture

Maryland's new shellfish lease laws became effective in 2009, removing many impediments that formerly restricted industry growth. Maryland additionally developed an infrastructure of training, permitting, and loan programs that support shellfish aquaculture development. These programs and other incentives provided increased opportunity for the industry to grow and have resulted in documented positive impacts for our State.

Maryland currently has a vibrant industry with a total of 318 shellfish aquaculture leases on 3,993 acres that are actively being used by growers to plant and produce oysters and clams. In 2014, DNR has permitted and registered 498 distinct individuals to engage in shellfish aquaculture activities on and associated with these leases; and leaseholders have produced, harvested, and sold nearly 30,000 bushels of oysters. Within the next 5 years, the number of farms could expand by 50% and production is expected to double.

As a relatively nascent industry in Maryland, oyster aquaculture valuations are not currently available, but a 2013 MD Department of Legislative Services report (http://dls.state.md.us/data/polanasubare/polanasubare_natresenvntra/Fostering-Shellfish-Aquaculture-Production-in-Maryland-and-Other-States.pdf) on fostering oyster aquaculture in Maryland, shows that in 2010, national oyster aquaculture value was nearly $112 million and combined shellfish aquaculture production in Virginia in 2011 was approximately $35 million.

Maryland's Investments in Oyster Restoration and Sanctuaries

In addition to promoting oyster aquaculture, Maryland is investing millions of dollars in restoring the wild oyster population in Chesapeake Bay. Part of this restoration effort involves creating oyster sanctuaries from which oyster catches are prohibited. In September, 2010 the MD DNR implemented the Oyster Restoration and Aquaculture Development Plan, increasing oyster sanctuary areas from 9% to 24% of the remaining oyster bar habitat. The action was based on the recommendations from Maryland's Oyster Advisory Commission and a 6-year State/Federal Programmatic Environmental Impact Statement for restoring the Chesapeake Bay's oyster resource and industry published in June, 2009. The sanctuary network is designed to:

- protect half of the bay's most productive oyster grounds;
- provide essential ecological functions that cannot be obtained from areas where oyster harvest occurs;
- serve as a reservoir of reproductive capacity, generating larvae to populate other areas, including public oyster fishery areas;
- provide a broad geographic distribution across all salinity zones;
- increase our ability to protect these important areas from poaching; and
- facilitate development of natural disease resistance, the long-term strategy for restoring oysters.

The potential effects of ocean acidification on oysters, and the oyster reef communities that rely on these ecosystem engineers, needs to be considered in the coming years.

Monitoring of Ocean Acidification in Maryland

The Chesapeake Bay is arguably one of the most monitored bodies of water in the world. There are significant historical, as well as temporally and spatially intensive data sets available to assess nutrient and sediment pollution, the resulting algal blooms and hypoxia, and changes that have occurred due to various management actions and natural conditions. However, other regions of the State's waters are monitored less intensively and data to fully assess the impacts of acidification are lacking.

Current Monitoring Programs

Maryland's DNR and MDE are responsible for monitoring varying aspects of water and habitat quality in Maryland's waters. DNR's Resource Assessment Service measures ambient water quality conditions that affect the habitat of living organisms such as fish, oysters, crabs, and underwater grasses. Figure 5 shows most DNR tidal Chesapeake Bay and Coastal Bay monitoring sites in 2014. Parameters sampled include water temperature, salinity, dissolved oxygen, turbidity/water clarity, pH, chlorophyll and algal blooms, and various fractions of nutrients (e.g., nitrogen and phosphorus), and water column sediment. DNR maintains a network of fixed stations throughout the Chesapeake Bay and its tributaries, which have been monitored by boat or bridge, monthly or twice monthly, since 1985. Similar monitoring sites were established in Maryland's Coastal Bays starting in 1999. However, Figure 5 also highlights the lack of sampling in the coastal ocean.

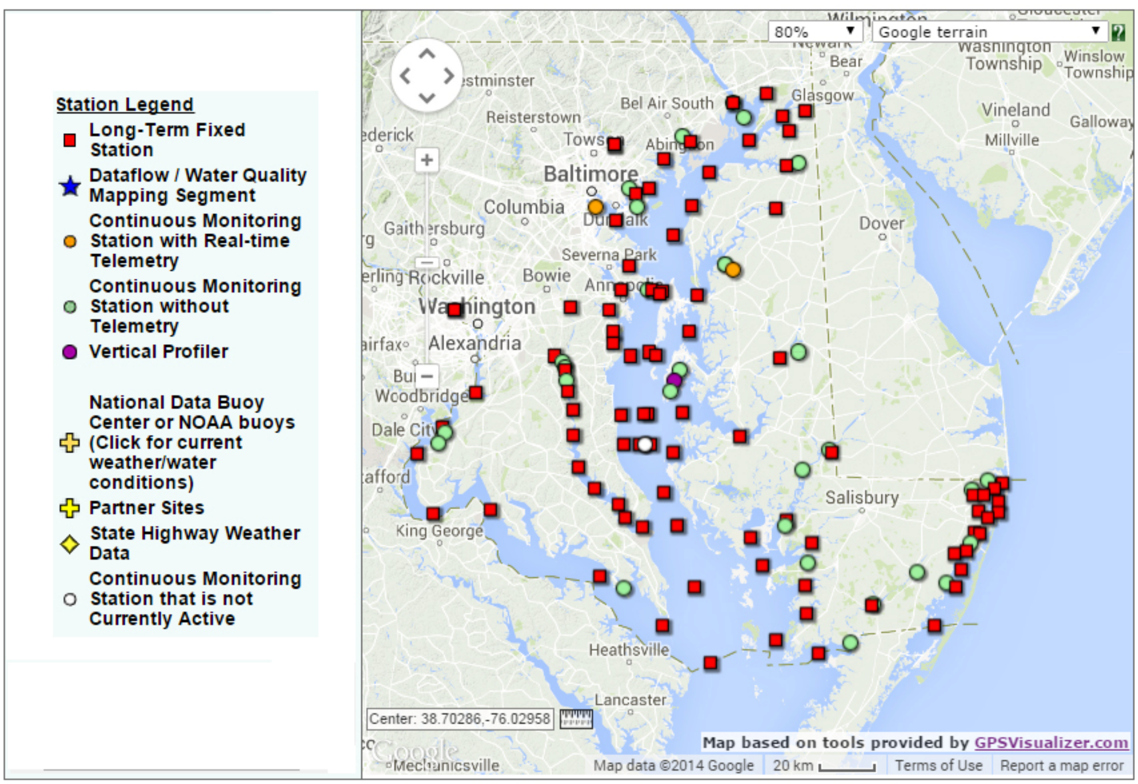

Figure 5. Map of 2014 MD DNR tidal water quality monitoring sites.

Since 2001, DNR has operated enhanced monitoring in the Chesapeake and Coastal Bays to aid in assessing water quality criteria. The enhanced monitoring includes automated continuous monitoring sites, mostly in waters of two meters of depth or less, that take readings of water temperature, salinity, dissolved oxygen, pH, chlorophyll, and turbidity every 15 minutes. The program also includes intensive monthly surface mapping of the same water quality parameters. The enhanced monitoring generally is performed in a three-year cycle in a tributary or Bay segment, with the exception of some sentinel areas where monitoring has occurred for ten or more years.

Bay-wide monitoring is coordinated by the EPA Chesapeake Bay Program (CBP) and its state partners. As a result, Virginia conducts similar monitoring programs with identical protocols that assure compatibility of data across the Chesapeake Bay. MD DNR data and subsets are available through the CBP datahub (www.chesapeakebay.net), DNR Eyes on the Bay website (www.eyesonthebay.net), EPA Water Quality Exchange (WQX), as well as internal DNR and MDE databases.

MDE monitors shellfish (oysters and clams) harvesting waters of the Atlantic Ocean, Coastal Bays, Chesapeake Bay, and tributaries monthly to meet the requirements of the National Shellfish Sanitation Program, safeguard the seafood industry, and protect public health. The monitoring stations are designed to provide water quality information directly related to shellfish harvesting areas and have been expanded to collect information at new aquaculture sites. These data and other data are used to classify shellfish growing areas to determine areas safe for the commercial harvest of shellfish. The classification of waters and sanitary control of shellfish assures public health protection for consumers.

Within the shellfish program, water samples are collected monthly under a stratified random sampling schedule that assures that samples are collected under a variety of conditions. MDE currently collects water samples at 762 active stations throughout the Bay (Figure 6). These samples are analyzed by the Department of Health and Mental Hygiene for fecal coliform bacteria. At all stations, MDE collects in situ weather, rainfall, and air and water temperature data. At a smaller subset of stations (221 of the active stations) staff also measures the surface and the bottom dissolved oxygen, pH, and salinity. Turbidity and clarity depths are also estimated. The shellfish harvesting water quality database has a continuous data record going back to the early 1970s.

The two primary Maryland monitoring networks are designed for different purposes and therefore have different collection requirements and station locations. As stated previously, the DNR program collects water quality information in the Bay and its tributaries, and MDE collects information at stations representing the shellfish growing areas. That said, both programs are lacking in key parameters used to assess the carbonate chemistry system of the Chesapeake Bay and measure the changes caused by acidification. At least two of the following four parameters need to be assessed to provide a basic understanding of carbonate chemistry: partial pressure of CO_2 (pCO_2), pH, total alkalinity (TA), and dissolved inorganic carbon (DIC). Ideally, measuring and

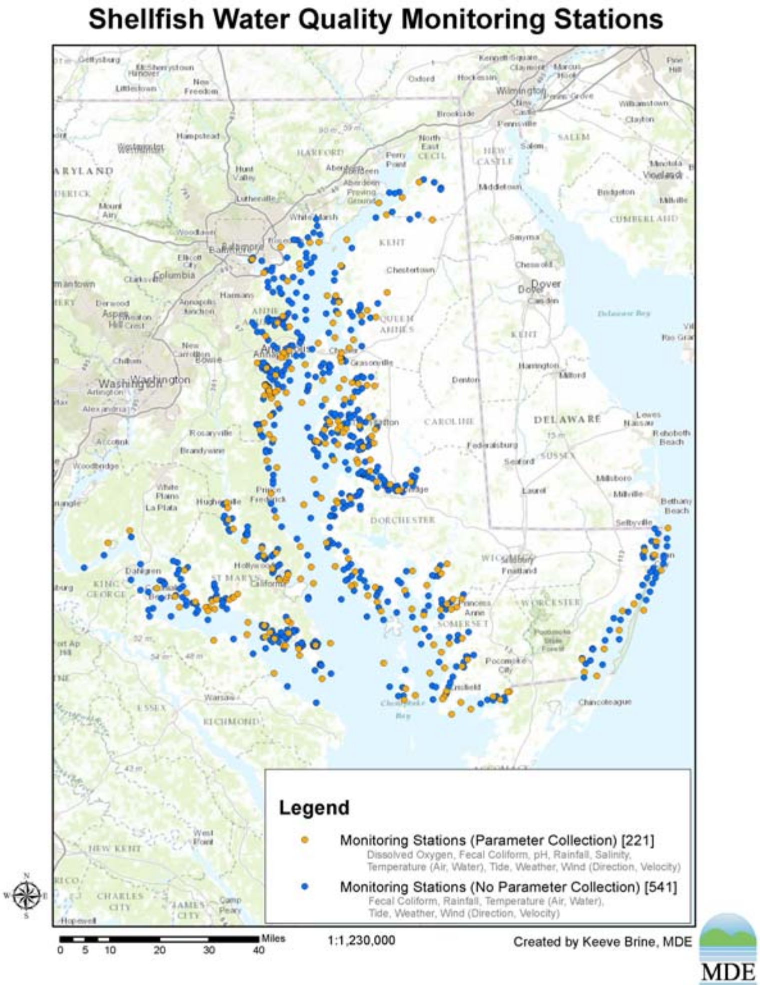

Figure 6. MDE Shellfish Monitoring Sites.

tracking all four parameters would increase the accuracy of any conclusions about the water chemistry, but this is not always feasible or cost-effective. Current technology allows for pH and pCO_2 to be measured autonomously and thus more cost efficiently and ubiquitously. However, recently published research indicates (Waldbusser et al., 2014) that aragonite saturation state (Ω) measured via TA may be the key variable that affects development of bivalves and would be important to quantify for these organisms. Currently in Maryland, continuous pCO_2 measurements are only being collected at the Smithsonian Environmental Research Center in Edgewater, MD and the Chesapeake Biological Laboratory in Solomons, MD.

On March 11-13, 2014, the Alliance for Coastal Technologies held a workshop entitled, "Science Assessment of Chesapeake Bay Acidification; Toward a Research and Monitoring Strategy." The workshop brought together scientific, monitoring, and management experts from the region and federal government to explore the current scientific knowledge and gaps in carbonate chemistry and acidification monitoring, and how acidification might affect coastal marine and estuarine waters. Their workshop report is available at the MD Ocean Acidification Task Force's website, http://mddnr.chesapeakebay.net/mdoatf/docs.cfm, and is an important companion document to this report, providing detailed scientific information and recommendations.

The existing DNR and MDE monitoring networks could serve as an effective backbone upon which to launch additional carbonate and acidification monitoring. There are additional federal and regional assets that could lend support. At the federal level, NOAA's Ocean Acidification Program (http://oceanacidification.noaa.gov/Home.aspx), which was established by the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM) (http://oceanacidification.noaa.gov/AboutUs/FOARAMAct.aspx), focuses on the following six areas:

1. MONITORING the changes in ocean chemistry.
2. Measuring the BIOLOGICAL RESPONSE of ecologically and economically important species.
3. Assessing the SOCIO-ECONOMIC IMPACTS of the changes and responses.
4. Monitoring DATA STREAMS & MANAGEMENT.
5. Assisting to create and implement ADAPTATION STRATEGIES.
6. Coordinating and conducting EDUCATION & OUTREACH.

The Interagency Working Group on Ocean Acidification (IWGOA), (http://oceanacidification.noaa.gov/IWGOA.aspx) which was also formed by FOARAM, developed the "Strategic Plan for Federal Research and Monitoring of Ocean Acidification" (ftp://ftp.oar.noaa.gov/OA/IWGOA%20documents/IWGOA%20Strategic%20Plan.pdf). The plan "will guide research and monitoring investments that will improve our understanding of ocean acidification, its potential impacts on marine species and ecosystems, and adaptation and mitigation strategies." At a regional level, the Mid-Atlantic Regional Coastal Ocean Observing System (MARACOOS), a regional association of the U.S. Integrated Ocean Observing System, along with NOAA Chesapeake Bay Program Office could lend support with existing monitoring buoy networks and assets. NOAA's National Estuarine Research Reserve System (NERRS), also provides support to Maryland and Virginia to maintain water quality data collection at several locations within the watershed.

The Chesapeake Bay region can also apply lessons learned from other ocean acidification monitoring networks that have already been established in California (C-CAN), the Northeast U.S. (NE-CAN), and the Southeast U.S (SE-CAN): (http://oceanacidification.noaa.gov/EngagementActivities/USRegionalNetworks.aspx).

Direct and Indirect Effects of Ocean Acidification on the Species and Ecosystems in Maryland State Waters

Ocean acidification will have substantial direct and indirect effects on the species and ecosystems of the Chesapeake Bay, Coastal Bays, and near-shore coastal ocean. The principal direct effects of ocean acidification on Maryland State waters arise from pH-dependent changes in carbonate chemistry that affect invertebrate animals such as oysters and crabs that incorporate calcium carbonate in their shells (Waldbusser et al., 2011b). More acidic conditions cause shifts in carbonate chemistry that make it harder for animals to form shells, thereby leading to thinner shells in bivalves such as oysters and clams (Waldbusser et al., 2010). But the direct effects of acidification are not restricted to just shelled-bivalves. Direct effects of acidification on the growth and survival of plants and animals that occur, or are similar to those common in coastal ecosystems within Maryland State waters, have also been reported (Hauton et al., 2009; Ries et al., 2009; Murray et al., 2014).

Indirect effects of acidification have also been reported that affect rates of production (Huesemann et al., 2002) and the outcome of predator-prey interactions (Bibby et al., 2007; Fabry et al., 2008; Amaral et al., 2012), which can substantially alter the structure and function of estuarine and coastal ecosystems. Moreover, whereas in the open ocean the direct effects of acidification typically occur in isolation from other environmental stresses, the presence of acidified waters in estuarine and coastal waters often co-occurs with other environmental stresses such as low dissolved oxygen (Melzner et al., 2013) or contamination (Roberts et al., 2013) so that the degree to which the direct effects of acidification are expressed can be magnified or dampened by the interactions with the other stresses. In particular, elevated temperatures, low dissolved oxygen concentration, and altered food webs can exacerbate effects of acidification (Parker et al., 2012; Gobler et al., 2014; Pedersen et al., 2014) and will likely be of concern in the warm, eutrophic Chesapeake and Coastal Bays. The interactions among these stressors are often non-linear which makes forecasting the overall effects of acidification challenging.

Part of the challenge of assessing the impacts of acidification on Maryland State waters is that most of the research on acidification and its impacts has focused on open ocean species and ecosystems (i.e. Ocean Acidification v1.0). Considerably less work has focused on the estuarine and coastal ecosystems that typify Maryland's State waters (i.e. Ocean Acidification v3.0). This research gap is due in part to the complex spatial and temporal variability in pH that occurs naturally in these waters (Duarte et al., 2013). For example, the salinity gradients, which are a prominent feature of the Chesapeake and Coastal Bays, greatly alter the calcite saturation constant (Figure 7 - Miller et al., 2009). Under current conditions, most of Maryland's portion of the Chesapeake Bay are not saturated with respect to aragonite (i.e., $\Omega < 1$). Minerals, such as argonite, are most easily deposited when they are fully saturated in the water. So, in unsaturated conditions, calcified shells of animals such as oyster and clams slowly dissolve.

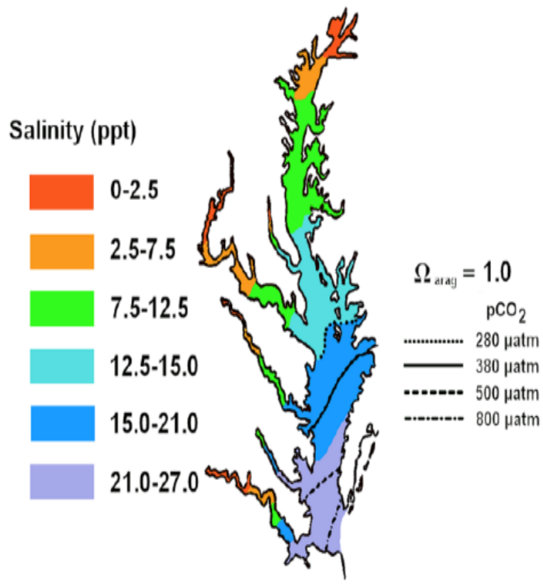

Figure 7. Map of the saturation state of aragonite (Ω) under current and future climate scenarios. The map also shows the relationship between salinity and the aragonite saturation level (Ω =1) under different atmospheric levels of CO_2 (From Miller et al. 2009).

Currently the dissolution of the shell is more than compensated by the addition of new material from growth. This means that any factor that slows the animal's growth makes shell dissolution more likely and thus will exacerbate the negative impacts of acidification. This further reinforces the importance of understanding the interactions among environmental stresses suggested previously, rather than examining their effects individually on a case by case basis. Future climate projections of increased pCO_2 shift the aragonite saturation isocline southward, implying that consideration of the balance of shell growth and dissolution will be a concern for a larger fraction of the Bay. This further reinforces the need to consider acidification as one component of a suite of environmental changes associated with climate change facing Maryland's State waters.

Effects of ocean acidification on species and ecosystems in estuarine and coastal waters of particular relevance to the Chesapeake and Coastal Bays

Maryland State waters are home to a wide diversity of plants and animals, and each likely show a species-specific response to acidification and other environmental stresses. However, knowledge to forecast the impacts of acidification on each of these species is currently lacking. Accordingly, focused attention on species viewed as important for either economic or ecological reasons can be used to draw inferences about broad impacts on other species.

Eastern Oyster (*Crassostrea virginica*)

Oysters are ecological engineers. They build reefs that modify the local physical and chemical conditions and provide home to a diverse array of species. Oyster aquaculture is also expanding in State waters. Importantly, because oysters are sessile, benthic animals that cannot move to avoid stressful environmental conditions, they have to either "hold their breath" and close their valves, or develop physiological adaptations. As a result, oysters can serve as a "canary in the coal mine" for environmental stress. For all of these reasons, understanding the impacts of acidification on oysters is important to the ecological and economic services that can be taken from State waters.

Several researchers have examined acidification impacts on eastern oyster (hereafter oyster). Miller et al. (2009) were the first to show an impact of acidification on both growth and calcification rates in larval oysters. These authors reported that reductions in Ω (i.e., increased acidification) caused reductions in growth of larval oysters and reduced levels of aragonite in oyster shells. More recently, Keppel (2014) has shown that exposure to acidic conditions for only a few hours per day can reduce growth rates of oyster spat held at low salinities which are protective for diseases currently affecting Chesapeake Bay waters. Although these studies consider impacts only at the larval and juvenile stages, we note that studies in other oyster species have indicated that these early life impacts can carry through to affect survival and reproduction later in life. Elevated pCO_2 levels have also been shown to shift protein expression in oyster tissues (Tomanek et al., 2011) and susceptibility to oxidative stress (Matoo et al., 2013). Several researchers have shown effects of elevated pCO_2 levels on the mineralization of oyster shells (Waldbusser et al., 2011a; Waldbusser et al., 2011b; Ivanina et al., 2013). Fresh shells from local shucking houses were affected more by acidification than weathered (~ 2 yr old) oyster shells (Waldbusser et al., 2011a). The effect of shell aging on variation in dissolution rates was of a similar magnitude to that developed by variable pH.

Research has found that interactions among acidification, salinity, and temperature had energetic and survival costs for oyster (Dickinson et al., 2012; Ivanina et al., 2013; Matoo et al., 2013). Waldbusser et al. (2011b) showed that declines in pH observed in the mesohaline (salinity >5 and <18ppt) regions of the Chesapeake Bay from 1985 – 2008 were of sufficient magnitude to cause changes in the structure of oyster shells (Figure 8). Moreover, the effect of pH was greater at lower salinities and lower temperatures (Waldbusser et al., 2011b), suggesting oysters in the Maryland portion of the Chesapeake Bay, and at the heads of the Coastal Bays may be at particular risk. Also of importance in this study was that increases in temperature reduced the impact of acidification, but in a non-linear fashion. Together research conducted to date indicates that ocean acidification can affect metabolism, growth, survival, and resistance to other environmental stresses of individual oysters.

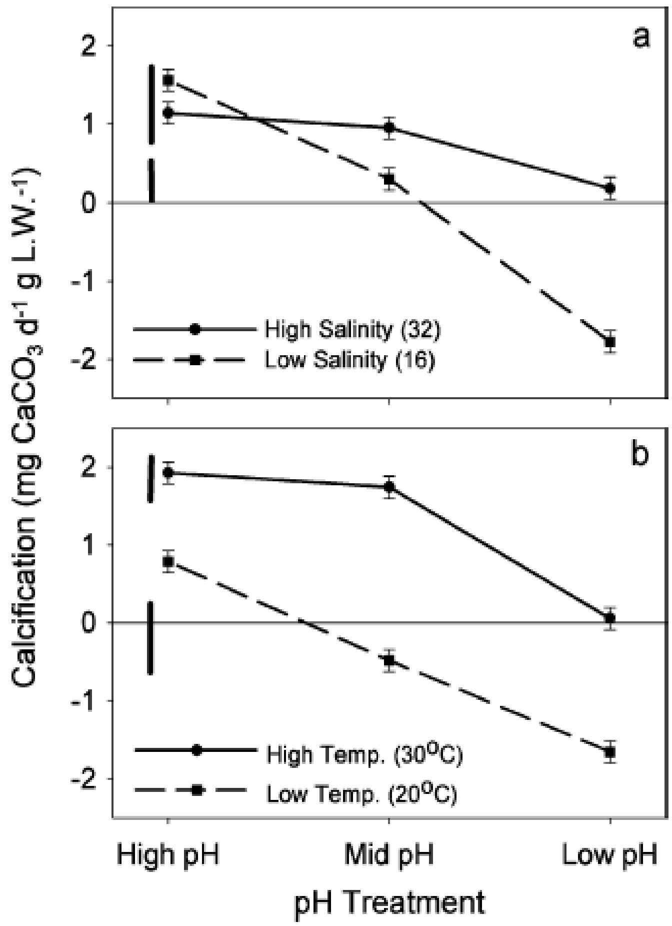

Figure 8. Biocalcification rates of oyster shell as a function of pH and temperature (From Waldbusser et al., 2011b). Of note are the declines in calcification under all acidified conditions.

Much of the importance of oysters to the ecology of Maryland State waters lies in their ability to build reefs. Years of historical overfishing, disease, and habitat loss (Rothschild et al., 1994; Wilberg et al., 2011) decimated the once abundant reefs in Maryland State waters. The loss of this important ecosystem engineer and the habitat it generates has had important consequences to estuarine ecosystems within the State (Kemp et al., 2005), which has led to substantial investments to restore oyster reefs and the ecosystem they support (Fulford et al., 2010; Gutierrez et al., 2011). Recently, Waldbusser et al. (2013) explored reef wide impacts of acidification. These authors found that oyster reefs represent a balance between the accumulation of calcium carbonate in older, larger oysters which reduce the alkalinity of the surrounding water, and the dissolution of the shells of dead oysters which regenerates the alkalinity. Ocean acidification upsets this balance, making the maintenance or growth of oyster shells more energetically demanding. Accordingly, acidification has the potential to alter the rate at which oyster reefs accrete biomass. Although considerable work has been conducted to explore the response of individual oysters to acidification, little work has been completed that explores the effects of acidification on the overall shell budgets of estuarine ecosystems. Yet, the results of such studies have important consequences for restoration efforts at the ecosystem scale.

Interest in oyster aquaculture is also growing within Maryland. On the U.S. West Coast, ocean acidification has been shown to have important economic impacts on the aquaculture industry (Barton et al., 2012). Barton and colleagues (2012) demonstrated that production of Pacific oyster (*Crassostrea gigas*) was negatively impacted by acidification of incoming sea water. Barton and colleagues showed impacts on both growth and production of larval Pacific oysters. Concerns over the impact of acidification on west coast aquaculture led to a study by blue ribbon panel of experts in Washington State (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). This panel concluded that aquaculture in Washington was particularly vulnerable both because of the oceanographic conditions off the Washington coast that give rise to pulses of acidified water that is upwelled from depth and because the majority of the aquaculture species in Washington are simple calcifying animals.

Oyster aquaculture in Maryland may be similarly vulnerable to acidification, but it is important to note the important differences between the situation in Maryland and on the West Coast. First, as already discussed, acidification in estuaries and coastal waters is governed by different processes than in the coastal ocean. Therefore, it is unlikely that the pattern and duration of pulses of acidic water observed in Washington aquaculture facilities will be experienced in Maryland. This means that engineering solutions recommended in the Washington study may not be effective in Maryland. Second, oyster aquaculture in Maryland has to deal with multiple environmental stresses that will likely interact to affect the productivity of aquaculture facilities.

Blue Crabs

Blue crabs (*Callinectes sapidus*) support another valuable fishery in Maryland State waters. Like oysters, crabs incorporate calcium carbonate into their shell (carapace). However, there are two important physiological and biochemical differences between how crabs and oysters use calcium carbonate. Key to these differences is that crab shed their carapaces as they grow, and each time they have to mobilize and redeposit calcite. However, once the carapace is formed, the calcite incorporated within it is somewhat protected from the external chemical environment as crabs regulate their body chemistry, whereas the calcium carbonate in oyster shell is external to the body and directly exposed to the external chemical environment.

Moreover, whereas oysters utilize carbonate ions (CO_3^{2-}) in depositing calcium in their shells, crabs utilize bicarbonate ions (HCO_3^-) in depositing calcium in their carapaces. Importantly, acidification will cause shifts in the carbonate system that make carbonate ions less available, thereby reducing mineralization of oyster shell described above. In contrast, these same changes will make bicarbonate more available, suggesting that calcification rates in blue crab may increase. Indeed, Ries et al. (2009 – Figure 9) inferred increased calcification in blue crab exposed to acidified conditions, although recent work by Lane et al. (pers. comm.) questions this conclusion.

A considerable body of work has been conducted on the role of pH in molt cycle of blue crab, but this work sought to examine physiological processes involved in the mobilization and re-deposition of calcium carbonate in the carapace under normal environmental conditions (Cameron and Batterton, 1978; Mcmahon et al., 1983; Cameron, 1985; Cameron and Wood, 1985; Mangum, 1985; Neufeld and Cameron, 1994). Much of this work emphasizes the role that control of the internal pH of crab body fluids has on calcification. This suggests that under acidified conditions the energy crabs expend to maintain this regulated internal environmental will change. However, the overall impact of acidification on the energy required to support molting, growth and survival in blue crab remains unclear. Indeed, very little work has been conducted on the effects of environmental acidification on blue crab. As a result, we rely here more on comparative studies of other crabs than we did for oyster.

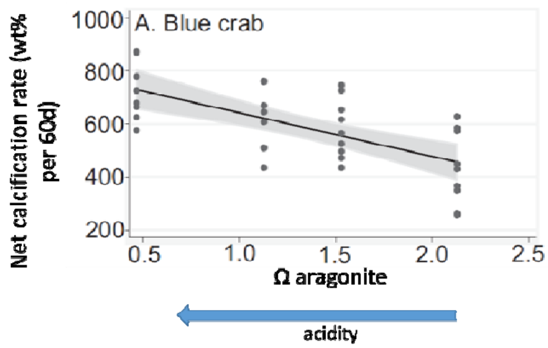

Figure 9. Calcification rates of blue crab as a function of pH (from Ries et al. 2009).

Blue crab exhibit a complex life history in which larvae occur in the coastal ocean (salinities >26 ppt) and juvenile and adults in estuarine and coastal waters. As a result, blue crab larvae are impacted more by acidification caused by considerations of pCO_2 equilibria, whereas juveniles and adults are exposed to the more dynamic estuarine pH environment. No work has been conducted on the effects of acidification on blue crab early life history. Comparative studies on larvae of other crab species have shown impacts on morphology, growth, and survival (Walther et al., 2010; Walther et al., 2011; Long et al., 2013a; Long et al., 2013b). Under acidified conditions crabs exhibited longer larval durations (Walther et al., 2010; Long et al., 2013b), mineralization increased (Long et al., 2013a; Long et al., 2013b), and survival decreased (Long et al., 2013b). However, the crab species studied to date have been high latitude, cold water crabs whose entire life history is completed in marine waters. The relevance of these studies for blue crab remains unclear.

Acidification has been shown to impact juvenile and adult blue crab. As noted previously, Ries et al. (2009) inferred increased growth and calcification rates in crabs exposed to acidified conditions. Subsequently, these same authors indicated that there was no effect of acidification on the form of calcium carbonate in the carapace (Ries, 2011). Preliminary evidence from Lane et al. (pers. comm.) suggests no change in calcification rates in juvenile blue crab exposed to acidified conditions. Thus the impacts of acidification on calcification in blue crabs, remains uncertain. Indeed, studies on other crab species have also demonstrated variable impacts of acidification on calcification: no effect in red king crab (*Paralithodes camtschaticus*), but decreases in Tanner crabs (*Chionoecetes bairdi*) (Long et al., 2013). Examining growth impacts of acidification, Lane et al. (pers. comm.) recently reported no effect on how much crabs grow each time they molt, but increases in time between molts. These results parallel increases in stage duration seen in larval spider and king crabs described above. Lane's preliminary results suggest reductions in growth rates can be expected in response to acidification. These reductions in growth could increase the time to maturity, or decrease the size at maturity – both of which would reduce the overall fecundity and productivity of the population. As with oysters, crabs will likely be affected by multiple current and future environmental stressors simultaneously.

Unlike sessile oysters which can only respond to environmental stresses by closing their shells and "holding their breath" during periods when the water conditions are stressful, crabs can also move to avoid stress conditions. The widely reported crab jubilees, in which blue crab literally walk out of the water, are an example of how they move to avoid low oxygen water masses. In general low oxygen conditions tend to cause crabs to move to shallow water. Eggleston and colleagues (2005) have demonstrated that these movements increase cannibalism in blue crab by causing adult and juvenile blue crab to both occupy shallow water. It is not clear whether acidification may have similar effects. Increases in water temperature are likely to have important impacts on the blue crab that will interact with acidification. Crabs overwinter when temperatures drop below ~ 54 ^{o}F (12 ^{o}C). Current climate projects suggest that Maryland waters may warm sufficiently over the next 75 years such that crabs will no longer overwinter. Before this tipping point is reached, increases in temperature will shorten the period between molts. Over this same period, Maryland State waters will be experiencing acidification which as described will lead to increased periods between molts. The overall impacts on blue crab will result from the balance between the opposing impacts of these two stresses.

Striped bass

Striped bass (*Morone saxatilis*) is another iconic Maryland species. It supports important commercial and recreational fisheries in the Chesapeake Bay and the coastal ocean. The recent history of the striped bass population includes periods of abundance and periods of decline during which fishing bans were implemented. Like blue crab, striped bass exhibit a complex life history which takes them both into coastal ocean waters and estuaries. For striped bass, adults live in the coastal ocean and then make spawning migrations into estuaries (Peer and Miller, 2014). Larval and juvenile striped bass grow and develop in estuarine waters for their first year of life. Subsequently, most but not all adult striped bass join the migratory coastal stock (Secor 1992).

No recent research has been published dealing with effects of ocean acidification on striped bass. However, earlier research did explore the possibility of acidification as a cause of population declines in the early 1980s (Hall 1987), but it should be noted that many older laboratory studies raised pH by adding acid instead of CO_2, which could have different effects upon fish. Several hypotheses were suggested to explain the period of decline that led to the fishery moratorium in the mid-1980s, including one related to acidification of estuarine waters. This hypothesis invoked acid rain deposition lowering the pH of poorly buffered waters of eastern shore tributaries. The hypothesis posited that these conditions led to a direct effect of pH on larval striped bass growth and survival, but also an indirect effect involving increased mobilization of aluminum released from the sediments. Unpublished studies (Houde, pers. comm.) did show a direct but weak effect of pH on larval striped bass growth but a strong and direct effect on survival. Ultimately, research indicated that acidification was likely not the direct cause of the decline in striped bass abundance that led to the moratorium. No other research on the effects of ocean acidification on striped bass has been conducted outside of this early work on larval growth and survival.

Research has demonstrated impacts of ocean acidification on other species of fish which may have relevance for striped bass. Munday and colleagues (2009) have shown that elevated pCO_2 levels negatively impacted the ability of larvae of a tropical species to migrate to appropriate adult habitat. Subsequent research by Munday and colleagues (Devine et al., 2012) showed that migratory behavior of adult tropical fish could also be impacted by acidification. The mechanisms that adult striped bass use to find natal spawning areas is unknown and thus the extent to which this could be affected by acidification is also unknown. Fish sense or "hear" their environment using a series of fluid filled sensory sacs, each of which contains an otolith. Movement of the otoliths inside the sac, caused by noise of fish movement, excites sensory hairs that inform the fish of its position. Fish use these senses to detect habitats and orient correctly. Otoliths are accretions of calcium carbonate, and have been shown to be affected by acidification (Checkley et al., 2009; Bignami et al., 2013). In turn, acidification has been shown to have effects on the abilities of fish to select appropriate habitats (Simpson et al., 2011) and detect prey (Cripps et al., 2011). However, the specific impacts of acidification on striped bass have yet to be examined.

Forage Fishes

Management of forage fish (fish that serve as prey for other fishes) is receiving increasing focus (Pikkitch et al., 2012). These small fishes often control ecosystem structure, function and productivity (Essington and Munch, 2014). Thus potential impacts of acidification on these species may be important to the overall ecosystem health in Maryland State waters.

As noted for striped bass, there has been historical interest in the effects of acidification on some species of anadromous species (Hall 1987). Other important anadromous species include the shads and river herrings (including American shad and alewife and blueback herring, *Alosa spp.*). These species are currently at low levels of abundance, principally as a result of damming of rivers which were historical spawning areas and coastal intercept fisheries. However, work by Leach and Houde (1999) on American shad (*Alosa sapidissima*) indicated their susceptibility to acidification. Leach and Houde report that larval growth and survival was influenced by pH. Several recent studies have shown important effects of ocean acidification on other key forage species, including Atlantic and inland silversides (*Menidia menidia and M. beryllina*) which serve as prey for both piscivorous fishes and birds. Baumann et al. (2012) found exposure of *M. beryllina* embryos and newly hatched larvae to elevated pCO_2 greatly reduced average survival and length. Murray et al. (2014) found that *M. menidia* embryos and larvae were also sensitive to acidification, and that parental exposure influenced the sensitivity of offspring.

Recent work by Breitburg et al. (2015) has examined interactive effects of low dissolved oxygen and acidification, which are mechanistically linked because respiration simultaneously removes oxygen and adds carbon dioxide to water. As a result of this covariation in stressors, fish living in regions of the Chesapeake Bay or of coastal lagoons in which they experience hypoxic stress will likely simultaneously express low pH stress. Results of preliminary experiments indicate that elevated pCO_2 increases the sensitivity of both *M. menidia* and *M. beryllina* to hypoxia, perhaps because of the effect of pH on the oxygen-binding ability of blood pigments or increased energetic costs of obtaining oxygen in a hypoxic environment (Miller et al., pers. comm.).

Key Species Conclusions

Oyster Conclusions

This brief summary of the impacts of acidification on the biology of individual oysters and on the ecology of oyster reefs overall lead to several important conclusions.

1) *Increasing acidification threatens the sustainability of ecological oyster restoration efforts in Maryland State waters, and particularly in the Chesapeake Bay.*

   The aforementioned findings demonstrate the importance of changes in the chemical environment in Maryland State waters caused by acidification on shell growth. Regions in which the saturation constant for argonite (Ω) <1 are likely to expand under all scenarios of climate change. Oyster growth is more difficult in waters in which Ω <1, and these waters may ultimately lead to dissolution of oyster shell. The state and federal partners are making substantial financial investments in ecological oyster restoration. Acidification has the potential to impact the outcomes of these investments. In particular, ecological restoration efforts are most challenged in fresher, cooler regions of Maryland State waters.

2) *Increasing acidification threatens the sustainability of wild capture oyster fisheries in Maryland State waters.*

   Oysters have supported important capture fisheries since pre-colonial times. Continued sustainability of these fisheries is a core goal for State agencies. Sustainable fisheries management balances removals from the stock by the fishery with additions to the stock from growth and reproduction. Acidification has the potential to reduce oyster growth and reproduction. Therefore, acidification may alter sustainable fishing levels for oysters in Maryland State waters.

3) *Increasing acidification threatens the economic feasibility of oyster aquaculture in Maryland State waters and particularly in Chesapeake Bay.*

   Oysters are particularly vulnerable to the effects of acidification because they are simple calcifying organisms which cannot individually regulate the chemical conditions in which they deposit their shell material. Acidification has been shown to be detrimental to oyster growth and survival and, as a result, has the potential to negatively growth of oysters in aquaculture thereby impacting its economic viability.

4) *Current monitoring programs are insufficient at either a scale or frequency to effectively assess chemical changes in ways useful to water quality dependent industries like shellfish aquaculture.*

   In much of State waters, ocean acidification is driven by complex biogeochemical processes which cause high spatial and temporal variability in the location, persistence and intensity of ocean acidification. Therefore, monitoring efforts should be designed to reflect this scale of variability.

Blue Crab Conclusions

1) *Blue crab supports important fisheries in the Chesapeake Bay and throughout the Delmarva lagoons.*

2) *There is insufficient scientific study of potential implications of increasing acidity in Chesapeake Bay and near-shore coastal waters to understand potential risks to blue crab stocks and fisheries.*

Striped Bass Conclusions

1) *Although some older laboratory experiments have explored acidification impacts on striped bass, little is still known because those studies' methodologies did not lower pH through the addition of* CO_2*, a factor which can impact acid-base regulation in fish.*

2) *Research on other fishes suggest a complex suite of impacts of acidification is possible on physiology, growth, survival, and behavior of individuals that may be relevant to species in Maryland State waters.*

Forage Fish Conclusions

1) *Forage fishes are important to the Chesapeake Bay food web and are consumed by larger species that support fisheries and by birds.*

2) *There has not been sufficient scientific study of the effects of increasing acidity in Chesapeake Bay and near-shore coastal waters to predict risks to forage fish populations, but pH in Chesapeake Bay does reach levels shown to be harmful to early life stages of some shallow-water species.*

Ocean Acidification Threats and Responses Elsewhere in the US

Maryland is the first state in the mid-Atlantic to initiate a study and seek explicit recommendations to understand and address ocean acidification issues. But because the inherent driver of this problem is an overabundance of atmospheric carbon dioxide, which can be exacerbated locally by nutrient runoff pollution, other states and species are also impacted by this decrease in pH and carbonate ion concentration. Even though the specific fisheries and oceanography of these other, sometimes distant states, may seem less relevant to Maryland, the fact that some studies of species showing negative responses to acidification are taxonomically similar to those of Maryland should not be overlooked. In addition, the policy, management, and industry responses may help inform Maryland as well.

In the most compelling comparison, Oregon and Washington State experienced some of the most negative impacts of acidification to date. Between 2005 and 2009, substantial numbers of Pacific oyster larvae mysteriously died in aquaculture facilities in these states, and no immediate cause was apparent. During this time of uncertainty, one hatchery spent more than $250,000 to rid their stocks of a pathogen, although later Oregon State University and NOAA scientists determined ocean acidification caused the large mortality events (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). The comprehensive response to ocean acidification in this particular region will be discussed in a later section of this report, but as carbon emissions have not been reduced at local and global scales, this threat still lingers in the minds of these shellfish growers.

Local drivers of acidification are also a concern to these communities. A West Coast Ocean Acidification and Hypoxia Panel was formed in 2013 to explore to address the causes and possible responses to ocean acidification and hypoxia. Funded by the California, Oregon, and Washington State government agencies, this panel of scientists sought to provide decision-makers with information to help guide management and understanding on this complex issue and help coordinate a policy response (http://westcoastoah.org/).

To the north, Alaskan fishing communities have become concerned about acidification as well. Based on experiments conducted from 2009-2012, NOAA scientists concluded that the commercially important red king crab (*Paralithodes camtschaticus)* and Tanner crab (*Chionoecetes bairdi)* stocks were likely to be harmed by pH levels decreasing below current levels of 8.0 to the point where pH levels of 7.5 caused a 100% mortality of juvenile red king crabs (Long et al., 2013). Although ocean acidification is not simply measured by pH levels alone, scientific studies such as this one are a cause of concern for fishermen and coastal communities alike. Indeed, a 2014 socioeconomic study has shown that southwestern and southeastern Alaskan communities are extremely vulnerable to acidification because it will likely cause stock decreases in marine resources on which these communities heavily rely and few other economic opportunities exist (Mathis et al., 2014). In December 2014, a workshop was held in Anchorage to discuss the science and potential economic impact of acidification on local communities and fisheries, as well as potential responses using the Washington State Blue Ribbon Panel on Ocean Acidification Report as a guide (http://www.aoos.org/ocean-acidification-workshop/). Recommendations from the Washington State Panel are addressed in the next section entitled, "Analysis of Other States' Responses to Ocean Acidification". The findings from the Anchorage Workshop should be used to help inform Maryland fisheries industries on potential economic impacts from acidification.

Massachusetts is also starting efforts to understand and plan for the effects of acidification. The U.S. sea scallop (*Placoplecten magellanicus*) fishery, largely based out of southeast Massachusetts, is one of the highest-value single-species fisheries in the nation, and if acidification were to reduce scallop harvests by just 25%, this would translate into a loss of $67 million a year in revenue (Cooley and Doney, 2009). Specific communities, dependent on the scallop fishery, will likely feel the resulting economic losses more than others. Not coincidentally, a conference was held in New Bedford, MA in late October 2014 for researchers, decision-makers, fishermen, and community groups to discuss the potential local impacts of ocean acidification.

Summer flounder, a common sport fish in the mid-Atlantic has also been shown to be sensitive to drops in pH. NOAA researchers at the Howard Lab in New Jersey have found that embryos of summer flounder, the largest recreational fishery in New Jersey, experience increased mortality when exposed to high CO_2 levels. When exposed to these conditions, including a pH of 7.5, the fluke embryo mortality reached 52%, and at an extreme treatment of 7.1 pH, mortality reached 84% (Chambers et al., 2014). Moving forward, scientists at this lab plan to examine other species, the generational effects of exposure to CO_2, and the role of habitat in species resilience.

Much of the understanding about ocean acidification stems from the change in chemistry and its impact on specific marine species. From a policy interpretation, this has caused varying degrees of concern depending on the commercial importance of the affected species, however one aspect that is frequently absent from discussion involves the larger food web impacts brought on by acidification. Partially because these impacts are not well understood, and partially because the economic value of all the species and services are hard to quantify, does consideration of the larger ecosystem receive less attention than does a specific species. Still, researchers have begun to make strides understanding ocean acidification in a more comprehensive manner through theoretical modeling; for example NOAA researchers have modeled the impacts of ocean acidification on food webs in estuaries such as Puget Sound in Washington State (Busch et al., 2013), and in collaboration with other experts they have examined these impacts as they relate to key commercial species in fisheries off the West Coast (Kaplan et al., 2010). Studies of specific species in the wild, such as pteropods, at the base of the food chain are also beginning to supplement some of the theoretical understanding of this impact. In 2014, NOAA and university scientists concluded that these microscopic animals, a critical part of the lower level of the food chain, off the US west coast are currently dissolving due to acidification (Bednaršek et al., 2014). These calcifiers provide food for a number of commercially important species, such as juvenile salmon, but it is unclear to what extent they comprise the diet of predators and whether other prey can be substituted. Further, acidification impacts to indicator species such as pteropods are important to track because of the broader changes to marine ecosystems they may indicate (Fabry et al., 2008).

Analysis of Other States' Responses to Ocean Acidification

While the phenomenon of ocean acidification has been a field of study amongst oceanographers for decades, changes across the vast expanses of relatively stable oceans yielded slow and infinitesimally small reductions in pH that required sophisticated instruments to even measure (NOAA Pacific Marine Environmental Laboratory Carbon Program: http://www.pmel.noaa.gov/co2/story/Ocean+Acidification). However, oceanography becomes considerably more complex where winds and coastal currents interact with continental land masses, freshwater and pollutants from human land uses (20 Facts about Ocean Acidification, Woods Hole Oceanographic Institution, November 2013, http://www.whoi.edu/fileserver.do?id=165564&pt=2&p=150429).

Researchers from University of Washington developed initial scientific findings on the phenomenon of low pH ocean waters being created at depth by solution of atmospheric carbon dioxide and coastal water acidification expressed through ocean upwelling conditions unique to the U.S, West Coast (OA in the Pacific Northwest, Jan Newton and Terrie Klinger, University of Washington, 2014, http://coenv.washington.edu/research/major-initiatives/ocean-acidification/ocean-acidification-in-the-pacific-northwest/). From 2004-2009, Washington's lucrative shellfish aquaculture industry began to feel the presence of corrosive waters from these upwelling events through catastrophic oyster hatchery losses resulting in several seasons of high mortality and lack of a natural oyster spat set (Grossman, Northwest Oyster Die-offs Show Ocean Acidification Has Arrived, Yale Environment 360 Report, November 21, 2011, http://e360.yale.edu/feature/northwest_oyster_die-offs_show_ocean_acidification_has_arrived/2466/).

Pioneering leadership amongst the State's Governor, legislature, Native American Tribes and congressional delegation led Washington to be the first state to develop comprehensive recommendations to address ocean acidification research, monitoring, adaptation, and mitigation. Washington State's Blue Ribbon Commission on Ocean Acidification produced a first of its kind report published in November 2012.

Recommendations from the Washington report fell into 6 major categories:

1. Reduce emissions of carbon dioxide.
2. Reduce local land-based contributions to ocean acidification.
3. Increase our ability to adapt to and remediate the impacts of ocean acidification.
4. Invest in Washington's ability to monitor and investigate the causes and effects of ocean acidification.
5. Inform, educate and engage stakeholders, the public and decision makers in addressing ocean acidification.

6. Maintain a sustainable and coordinated focus on ocean acidification.

The Washington State Report can be found at the following link:
http://www.ecy.wa.gov/water/marine/oa/2012report_summary.pdf

The findings of that report were shared widely among coastal states in the US, especially states that also have bivalve shellfish aquaculture industries. California and Oregon formed a West Coast Acidification and Hypoxia Science Panel in 2013 (Fansler, 2013). By March of 2013, the Maine legislature passed resolution SP0559 (http://www.mainelegislature.org/legis/bills/bills_126th/billtexts/SP059901.asp), declaring ocean acidification to be a direct threat to the State's economy, largely because of the clam, mussel, and lobster fisheries.

The Maine Ocean Acidification Study Commission's draft report was released December 1, 2014 and will be presented to the Maine State Legislature after final edits are incorporated. Those recommendations include:

- Work with the federal government, fishermen, environmental groups, and trained citizens to actively monitor acidity changes in the water or sediments, and organisms' response to those changes.
- Conduct more research across various species and age groups to get a better sense of how acidification is affecting the ecosystem.
- Identify ways to further reduce local and regional emissions of carbon dioxide – a greenhouse gas produced by the combustion of fossil fuels – and to reduce runoff of nitrogen, phosphorus and other nutrients that can contribute to acidification.
- Reduce the impact of acidification through natural methods, such as increasing the amount of photosynthesizing marine vegetation like eelgrass and kelp, promoting production of filter-feeding shellfish operations, and spreading pulverized shells in mudflats with high acidity.
- Create an ongoing ocean acidification council to monitor the situation, recommend additional steps and educate the public. This recommendation is the only concrete legislative proposal contained within the report.

The Commission's full draft report is available at the following link:
http://www.maine.gov/legis/opla/OAreportdraft102114.pdf

While not all findings of the previous state reports will be relevant to Maryland waters, it has been extremely helpful for the Maryland Task Force to have the benefit of the analyses these states did before embarking on our own report. Some lessons learned for Maryland among the findings of other state task forces:

- Fundamentally, States realize the clear scientific link between this phenomenon and greenhouse gas emissions and that the effects of acidification are more rapid than other measures of climate change. Logically, each state should recognize the importance of continuing progress on accelerating greenhouse gas emission reductions.

- Recommendations from all reports identify key data gaps that must be filled by federal and state agencies and academic institutions. These data gaps are state or major water body-specific and must be developed within existing frameworks and with limited increased budgets.
- States are also realizing the important contribution of affected industries like fisheries and aquaculture as well as non-governmental advocacy organizations can play by being the eyes, ears and voice educating the public about biological changes in the system that have relevance to scientific measurements of water chemistry.
- Maryland is not subject to the same upwelling oceanographic conditions as the West Coast, although Chesapeake Bay can experience wind-driven seiching events where hypoxic bottom waters, lower in pH, are released towards the surface. Timing of hatchery or aquaculture operations could be coordinated to avoid deleterious impacts from these events.
- Overall, we can benefit from specific recommendations from the Washington report about reducing local land-based contributions which are likely to be significant here. These recommendations underscore current efforts throughout Chesapeake Bay and Coastal Bays to reduce nutrient loading from all sources that drive eutrophication of coastal waters.
- Washington's Chapter 6 recommendations may be very relevant for both Maryland's developing shellfish aquaculture operations and ongoing native oyster reef restoration initiatives, specifically, considering the vulnerability both have to risk of failure at the State's sole oyster hatchery.
- What we can also learn from these efforts is the importance of assigning responsible parties to each action, even if initial resources for those actions do not currently exist. Further, there is value in identifying a coordinating entity to ensure progress on the actions continues beyond the filing of the report.

Recommendations

The Task Force proposes recommendations in seven areas based on the findings and conclusions of the report.

Monitor Maryland State Waters to Quantify Scale, Pattern, and Trends of Ocean Acidification

Ocean acidification has the potential to negatively impact ecosystem restoration efforts, the emerging aquaculture industry, and certain fisheries in State waters. There is a need to inform the citizens of the State of potential implications of ocean acidification in magnitude (scale), where and when is it most likely to be experienced (pattern), and if it will get better or worse over time (trend). Therefore it is critical to collect the appropriate data to monitor the scale, pattern, and trends of ocean acidification to enable planning that could ameliorate or avoid its negative effects.

There is minimal oceanic monitoring in Maryland, and existing monitoring programs were not designed to quantify acidification and are inadequate to fully inform an understanding of or response to increasing acidification, particularly in estuarine (Chesapeake Bay) and lagoonal (Coastal Bays) waters, where other environmental factors combine with increasing carbon dioxide concentrations to increase frequency and magnitude of acidification events.

However, existing monitoring networks can be enhanced to provide effective data collection platforms.

- Based on a thorough review of all existing data collection programs for water quality, habitat monitoring, and industry practices; identify sites where either new sampling platforms or enhancements to existing platforms would increase understanding of the scale, pattern, and trends of acidification for the benefit of natural resource management, restoration efforts and affected industries.
- The State should develop and enhance cooperation with affected industries to allow them to host or otherwise support monitoring sites that will benefit industry and the State in understanding and responding to acidification events and trends.
- The State should work with all of its federal and state partners to coordinate monitoring programs throughout state and regional waters. Cooperative efforts and funding opportunities should be pursued with the EPA Chesapeake Bay Program, the NOAA Ocean Acidification Program, the NOAA Chesapeake Bay Program Office, and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS). Maryland's leadership and commitment to understanding acidification impacts to Maryland waters along with the legislative initiative to form the Task Force to Study the Impacts of Ocean Acidification on State Waters will enhance federal funding opportunities.

Identify Additional Research Priorities

The broader research community is just beginning to more thoroughly and effectively investigate the impacts and interactions of acidification in dynamic estuarine and coastal environments. It is recognized that beyond just geochemical/atmospheric inputs of carbonates (Ocean Acidification v1.0), and deep sea upwelling and mixing of carbonate rich waters (Ocean Acidification v2.0) that contribute to acidification, estuaries and coastal waters are characterized by complex carbonate budgets resulting from biological processes, nutrient enrichment, and terrestrial influences (Ocean Acidification v3.0). Research efforts in Maryland should be focused on the characterizing the carbonate budget in Maryland State waters and its impacts on ecosystem, with particular focus on key commercially- and ecological-important species. We recommend priority research areas that focus on the following sources and consequences:

- Quantify the sources of acidification and their relative contributions to the problem in Maryland waters.
- Understand the alkalinity budget of Maryland State waters.
- Quantify the compounding effects of low dissolved oxygen, nutrient enrichment, increased temperature, and altered food webs in tandem with acidification.
- Understand the consequences of the carbonate balance to oyster and shellfish communities, and the contributions that oyster restoration efforts may have in improving the buffering capacity of the Maryland State waters.
- Quantify the impacts of acidification on individual key commercially- and ecologically-important species with respect to impairment of reproduction, growth, and survival.
- Quantify the complex ecosystem interactions that are occurring throughout the food chain, including impacts to the habitat and early life stages of commercially important species, as well as forage fishes and plankton.

Improve Coordination with Other States and Federal Resource Managers

Ocean acidification is an international issue with local impact, therefore coordination with other states and federal entities is crucial.

- Maryland should seek to become the study locale for ocean acidification 2.0/3.0 projects, by applying to NOAA for funds to study impacts in estuarine systems. The timing is opportune both in federal interest and funding.
- Maryland should join forces with states in other regions (e.g., New England and the Pacific Northwest) that have similar commissions or task forces on ocean acidification, for the purpose of bringing greater national attention to this issue, supporting expansion of the network of states actively engaged in this issue, sharing information on acidification research, monitoring and findings, and leveraging resources where appropriate.

- As hypoxia and acidification are driven by nutrient over-enrichment, Maryland should continue taking the lead in developing the new Chesapeake Bay Agreement Climate Change strategies, implementation of Chesapeake and Coastal Bays TMDL and WIP goals, and continuing full support of nutrient reduction strategies. While understanding is limited, there is evidence that addressing these compounding factors can help reduce impacts to valuable natural resources and affected industries.
- Work with international, national, and regional partners to advocate for a comprehensive strategy to reduce carbon dioxide emissions. Maryland's existing Greenhouse Gas (GHG) reduction initiatives as defined in the State's 2013 Greenhouse Gas Emissions Reduction Act Plan calling for a 25% reduction from a 2006 baseline in GHGs by 2020 should be fully supported and serve as the foundation for a comprehensive carbon dioxide reduction strategy.
- Enlist key leaders and policymakers to act as ambassadors advocating for carbon dioxide emissions reductions and protection of Maryland's aquatic resources from acidification.
- Maryland representatives to the Chesapeake Bay Program and Coastal Bays Program should coordinate efforts among watershed jurisdictions and help to expand research, monitoring, and attention to ocean acidification in the region.
- Maryland representatives to the Chesapeake Bay Commission should request that the Commission take a more active role in sponsoring watershed-wide action to reduce carbon dioxide emissions and educate stakeholders, the public, and decision makers on acidification issues.

Focus on Impacts to Key Species and Associated Activities
Acidifying conditions create particular concerns for some high value species. This section of recommendations speaks specifically to steps that should be taken to better understand implications to help mitigate loss or improve performance in key industry or conservation efforts.

- Oysters are of particular economic importance both through directly supporting wild stock and aquaculture production and indirectly in providing important habitat and other ecosystem services. Further, while impacted by acidifying conditions, oyster populations can also provide buffering capacity within aquatic systems.
    - Include aragonite saturation (Ω) as one of the possible criteria considered for oyster restoration site selection.
    - Support diversification of larval shellfish supply by increasing the number larval hatchery facilities.
    - Establish a robust monitoring and reporting system for the Horn Point shellfish hatchery to notify interested agency and industry partners.
    - Establish "best practices" for aquaculture facilities to respond to and mitigate acidification in State waters.

- Blue crabs are an iconic and commercially important species for Maryland, much as the lobster is in Maine.
  - Conduct research on the growth, survival and reproductive output of blue crab. Blue crab have calcified carapaces, but the physiological mechanisms underlying calcification in blue crab is different to that in oysters and clams and thus the response of blue crab may be different to those of oysters and clams.
  - Quantify the joint impacts of acidification and hypoxia on the distribution of blue crab within State waters and hence on the distribution of fishing effort.
  - Assess the impacts of acidification and climate change on the sustainability of the blue crab fishery. In particular, consideration should be given to the changes in the productivity of the stock on sustainable harvest levels.
  - Coordinate research efforts on the impacts of acidification on blue crab with neighboring states and federal partners (e.g., EPA Chesapeake Bay Program, NOAA Chesapeake Bay Office, and NOAA Office of Ocean Acidification).
- Striped Bass and other fishes
  - Assess the impacts of acidification on reproductive potential of striped bass and other economically important species.
  - Quantify the impacts of acidification on the growth and survival of early life stages of striped bass within estuarine spawning areas.
  - Assess the impacts acidification on possible changes in the distribution of migratory behavior of striped bass.
  - Evaluate possible impacts of acidification on sustainable exploitation rates of striped bass.
- Forage fishes
  - Quantify the impacts of acidification on the growth and survival of early life stages of key forage species including bay anchovy, Atlantic menhaden, shad and river herrings, and Atlantic and Inland silversides
  - Assess the impact of acidification on the potential for forage species to support the dietary needs of commercially- and ecologically-important piscivorous species (e.g., striped bass, weakfish, etc.)
  - Implement a zooplankton monitoring program designed to improve understanding of how acidification effect on phytoplankton will cascade through the food web to forage fish and ultimately dependent fisheries

Provide Direct Support to Affected Industries

Maryland businesses are investing heavily in increased aquaculture production. This business activity is dependent on healthy waters that continue to support oyster reproduction and growth. Additionally, while current hatchery activity is centralized around public hatchery production, as local production matures, private hatcheries are expected to play an increasing role in commercial production support. The Task

Force recommends the following to better support industry engagement in healthy and growing shellfish production:

- Develop a cooperative system of reporting by hatcheries and aquaculture facilities for mortality events, so that events can be detected, studied, and diagnosed more effectively; mitigation steps can be taken in a more timely fashion; and insight can be gained to prevent future occurrences.
- Educate local growers about and incorporate relevant mitigation strategies identified by the Washington State Blue Ribbon Panel on Ocean Acidification.
- As industry expands, focus on support to diversify the number and location of larval production hatcheries to hedge catastrophic loss.
- Support and encourage a voluntary monitoring system of minimum suite of key carbonate chemistry parameters with various industries and stakeholders at their facilities.
- Identify a lead for maintaining a database of key acidification monitoring and research findings.
- Establish regular information exchanges between science, management, and industry.

Pursue Legislative Action
A number of steps should be taken to implement the recommendations of this report:

- Maryland DNR should lead in establishing an interagency commission or workgroup with representation from the industry, State agencies (DNR/MDE), academic and research institutions (e.g., UMCES, SERC, and others), the Maryland Waterman's Association, the Chesapeake Bay Foundation, the Oyster Recovery Partnership, EPA Chesapeake Bay Program, and NOAA to implement recommendations, help identify additional resources, and report on the progress of interstate initiatives.
- Targeted funding should be secured for research priorities, enhanced monitoring, and coordination of activities with affected industries.
- A presentation by task force participants on ocean acidification should be given to the Chesapeake Bay Commission, for their consideration as a priority action item.

Improve Communications and Outreach
Communication is vital in helping targeted policy, management, and industry groups understand the science, the unique challenges in estuarine environments like the Chesapeake and Coastal Bays, and the risks to the ecosystem and economy.

- Maryland should develop a targeted outreach plan that provides information to watermen and coastal communities to encourage them to become engaged in planning and priority setting for responses to ocean acidification.
- Maryland should fund, build, and maintain a dynamic website to host this report, other relevant documentation, and future developments in ocean

- Leverage Maryland Sea Grant's outreach and education capabilities to raise awareness of ocean acidification, with particular attention to the shellfish aquaculture industry.

Appendix

Minutes, presentations and supporting resources for Maryland's 'Task Force to Study the Impact of Ocean Acidification on State Waters' can be found at the following website:

http://mddnr.chesapeakebay.net/mdoatf/index.cfm

Literature Cited

Alliance for Coastal Technologies. 2014. Workshop Proceedings of Science Assessment of Chesapeake Bay Acidification: Toward a Research and Monitoring Strategy, March 11-13, 2014. Publication [UMCES]CBL 2014-052 / ACT WS01-14.

Amaral, V., H. N. Cabral, and M. J. Bishop. 2012. Effects of estuarine acidification on predator-prey interactions. Marine Ecology Progress Series **445**:117-127.

Barton, A., B. Hales, G. G. Waldbusser, C. Langdon, and R. A. Feely. 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. Limnology and Oceanography **57**:698-710.

Baumann, H., S. C. Talmage, and C. J. Gobler. 2012. Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. Nature Climate Change **2**:38-41.

Bednaršek, N., R. A. Feely, J. C. P. Reum, B. Peterson, J. Menkel, S. R. Alin, and B. Hales. 2012. "Limacina helicina shell dissolution as an indicator of declining habitat suitability due to ocean acidification in the California Current Ecosystem."

Bibby, R., P. Cleall-Harding, S. Rundle, S. Widdicombe, and J. Spicer. 2007. Ocean acidification disrupts induced defences in the intertidal gastropod Littorina littorea. Biology Letters **3**:699-701.

Bignami, S., S. Sponaugle, and R. K. Cowen. 2013. Response to ocean acidification in larvae of a large tropical marine fish, Rachycentron canadum. Global Change Biology **19**:996-1006.

Breitburg, D.L., D. Hondorp, C. Audemard, R.B. Carnegie, R.B. Burrell, M. Trice and V. Clark. 2015 Landscape-level variation in disease susceptibility related to shallow-water hypoxia. PLOS ONE. *In press.*

Busch, D. S., C. J. Harvey, and P. McElhany. 2013. "Potential impacts of ocean acidification on the Puget Sound food web." ICES Journal of Marine Science: Journal du Conseil 70, no. 4: 823-833.

Cameron, J. N. 1985. Post-Molt Calcification in the Blue-Crab (Callinectes-Sapidus) - Relationships between Apparent Net H+ Excretion, Calcium and Bicarbonate. Journal of Experimental Biology **119**:275-285.

Cameron, J. N. and C. V. Batterton. 1978. Antennal Gland-Function in Freshwater Blue-Crab, Callinectes-Sapidus - Water, Electrolyte, Acid-Base and Ammonia Excretion. Journal of Comparative Physiology **123**:143-148.

Cameron, J. N. and C. M. Wood. 1985. Apparent H+ Excretion and CO_2 Dynamics Accompanying Carapace Mineralization in the Blue-Crab (Callinectes-Sapidus) Following Molting. Journal of Experimental Biology **114**:181-196.

Chambers, R. C., A. C. Candelmo, E. A. Habeck, M. E. Poach, D. Wieczorek, K. R. Cooper, C. E. Greenfield, and B. A. Phelan. 2014. "Effects of elevated CO 2 in the early life stages of summer flounder, Paralichthys dentatus, and potential consequences of ocean acidification." *Biogeosciences* 11, no. 6: 1613-1626.

Checkley, D. M., A. G. Dickson, M. Takahashi, J. A. Radich, N. Eisenkolb, and R. Asch. 2009. Elevated CO_2 Enhances Otolith Growth in Young Fish. Science **324**:1683-1683.

Cooley, S. R., and S. C. Doney. 2009. "Anticipating ocean acidification's economic consequences for commercial fisheries." Environmental Research Letters 4, no. 2: 024007.

Cripps, I. L., P. L. Munday, and M. I. McCormick. 2011. Ocean Acidification Affects Prey Detection by a Predatory Reef Fish. PLOS ONE **6**.

Devine, B. M., P. L. Munday, and G. P. Jones. 2012. Homing ability of adult cardinalfish is affected by elevated carbon dioxide. Oecologia **168**:269-276.

Dickinson, G. H., A. V. Ivanina, O. B. Matoo, H. O. Portner, G. Lannig, C. Bock, E. Beniash, and I. M. Sokolova. 2012. Interactive effects of salinity and elevated CO_2 levels on juvenile eastern oysters, Crassostrea virginica. Journal of Experimental Biology **215**:29-43.

Duarte, C. M., I. E. Hendriks, T. S. Moore, Y. S. Olsen, A. Steckbauer, L. Ramajo, J. Carstensen, J. A. Trotter, and M. McCulloch. 2013. Is Ocean Acidification an Open-Ocean Syndrome? Understanding Anthropogenic Impacts on Seawater pH. Estuaries and Coasts **36**:221-236.

Eggleston, D. B., G. W. Bell, and A. D. Amavisca. 2005. Interactive effects of episodic hypoxia and cannibalism on juvenile blue crab mortality. Journal of Experimental Marine Biology and Ecology **325**:18-26.

Essington, T. E. and S. B. Munch. 2014. Trade-offs between supportive and provisioning ecosystem services of forage fish in marine food webs. Ecological Applications **24**:1543-1557.

Fabry, V. J., B. A. Seibel, R. A. Feely, and J. C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science **65**:414-432.

Fansler, C. 2013. Wiley Rein LLP, Coastal States Respond to Ocean Acidification, December 5, 2013.

Fulford, R. S., D. L. Breitburg, M. Luckenbach, and R. I. E. Newell. 2010. Evaluating ecosystem response to oyster restoration and nutrient load reduction with a multispecies bioenergetics model. Ecological Applications **20**:915-934.

Gobler, C. J., E. L. DePasquale, A. W. Griffith, and H. Baumann. 2014. Hypoxia and Acidification Have Additive and Synergistic Negative Effects on the Growth, Survival, and Metamorphosis of Early Life Stage Bivalves. PLOS ONE **9**.

Gutierrez, J. L., C. G. Jones, J. E. Byers, K. K. Arkema, K. Berkenbusch, J. A. Commito, C. M. Duarte, S. D. Hacker, I. E. Hendriks, P. J. Hogarth, J. G. Lambrinos, M. G. Palomo, and C. Wild. 2011. Physical ecosystem engineers and the function of estuaries and coasts.*in* C. H. R. Heip, C. J. M. Philippart, and J. J. Middelburg, editors. Functioning of Estuaries and Coastal Ecosystems. Elsevier.

Hall, L. W. 1987. Acidification Effects on Larval Striped Bass, Morone-Saxatilis in Chesapeake Bay Tributaries - a Review. Water Air and Soil Pollution **35**:87-96.

Hauton, C., T. Tyrrell, and J. Williams. 2009. The subtle effects of sea water acidification on the amphipod Gammarus locusta. Biogeosciences **6**:1479-1489.

Huesemann, M. H., A. D. Skillman, and E. A. Crecelius. 2002. The inhibition of marine nitrification by ocean disposal of carbon dioxide. Marine Pollution Bulletin **44**:142-148.

Ivanina, A. V., G. H. Dickinson, O. B. Matoo, R. Bagwe, A. Dickinson, E. Beniash, and I. M. Sokolova. 2013. Interactive effects of elevated temperature and CO_2 levels on energy metabolism and biomineralization of marine bivalves Crassostrea

virginica and Mercenaria mercenaria. Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology **166**:101-111.
Kaplan, I. C., P. S. Levin, M. Burden, and E. A. Fulton. 2010. "Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management." Canadian Journal of Fisheries and Aquatic Sciences 67, no. 12: 1968-1982.
Kemp, W. M., W. R. Boynton, J. E. Adolf, D. F. Boesch, W. C. Boicourt, G. Brush, J. C. Cornwell, T. R. Fisher, P. M. Glibert, J. D. Hagy, L. W. Harding, E. D. Houde, D. G. Kimmel, W. D. Miller, R. I. E. Newell, M. R. Roman, E. M. Smith, and J. C. Stevenson. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. Marine Ecology-Progress Series **303**:1-29.
Keppel, A. G. 2014. The effects of co-varying diel-cycling hypoxia and pH on disease susceptibility, growth and feeding in *Crassostrea virginica* University of Maryland, College Park, MD.
Leach, S. and E. Houde. 1999. Effects of environmental factors on survival, growth, and production of American shad larvae. Journal of Fish Biology **54**:767-786.
Long W.C., K.M. Swiney, C. Harris, H.N. Page, and R.J. Foy. 2013. Effects of Ocean Acidification on Juvenile Red King Crab (*Paralithodes camtschaticus*) and Tanner Crab (*Chionoecetes bairdi*) Growth, Condition, Calcification, and Survival. PLoS ONE 8(4): e60959. doi:10.1371/journal.pone.0060959
Long, W. C., K. M. Swiney, and R. J. Foy. 2013a. Effects of ocean acidification on the embryos and larvae of red king crab, Paralithodes camtschaticus. Marine Pollution Bulletin **69**:38-47.
Long, W. C., K. M. Swiney, C. Harris, H. N. Page, and R. J. Foy. 2013b. Effects of Ocean Acidification on Juvenile Red King Crab (Paralithodes camtschaticus) and Tanner Crab (Chionoecetes bairdi) Growth, Condition, Calcification, and Survival. PLOS ONE **8**.
Mangum, C. P. 1985. Molting in the Blue-Crab Callinectes-Sapidus - a Collaborative Study of Intermediary Metabolism, Respiration and Cardiovascular Function, and Ion-Transport - Preface. Journal of Crustacean Biology **5**:185-187.
Mathis, J.T., S.R. Cooley, N. Lucey, S. Colt, J. Ekstrom, T. Hurst, C. Hauri, W. Evans, J.N. Cross, R.A. Feely, Ocean acidification risk assessment for Alaska's fishery sector, Progress in Oceanography, Available online 18 July 2014.
Matoo, O. B., A. V. Ivanina, C. Ullstad, E. Beniash, and I. M. Sokolova. 2013. Interactive effects of elevated temperature and CO_2 levels on metabolism and oxidative stress in two common marine bivalves (Crassostrea virginica and Mercenaria mercenaria). Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology **164**:545-553.
Mcmahon, B. R., P. L. Defur, C. P. Mangum, and M. G. Wheatly. 1983. Compensation for Changes in Acid-Base Status Occurring during the Molting Cycle in the Blue-Crab Callinectes-Sapidus. American Zoologist **23**:952-952.
Melzner, F., J. Thomsen, W. Koeve, A. Oschlies, M. A. Gutowska, H. W. Bange, H. P. Hansen, and A. Kortzinger. 2013. Future ocean acidification will be amplified by hypoxia in coastal habitats. Marine Biology **160**:1875-1888.

Miller, A. W., A. C. Reynolds, C. Sobrino, and G. F. Riedel. 2009. Shellfish Face Uncertain Future in High CO_2 World: Influence of Acidification on Oyster Larvae Calcification and Growth in Estuaries. PLOS ONE **4**.

Munday, P. L., D. L. Dixson, J. M. Donelson, G. P. Jones, M. S. Pratchett, G. V. Devitsina, and K. B. Doving. 2009. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. Proceedings of the National Academy of Sciences of the United States of America **106**:1848-1852.

Murray, C. S., A. Malvezzi, C. J. Gobler, and H. Baumann. 2014. Offspring sensitivity to ocean acidification changes seasonally in a coastal marine fish. Marine Ecology Progress Series **504**:1-11.

Neufeld, D. S. and J. N. Cameron. 1994. Effect of the External Concentration of Calcium on the Postmolt Uptake of Calcium in Blue Crabs (Callinectes-Sapidus). Journal of Experimental Biology **188**:1-9.

Parker, L. M., P. M. Ross, W. A. O'Connor, L. Borysko, D. A. Raftos, and H. O. Portner. 2012. Adult exposure influences offspring response to ocean acidification in oysters. Global Change Biology **18**:82-92.

Pedersen, S. A., O. J. Hakedal, I. Salaberria, A. Tagliati, L. M. Gustavson, B. M. Jenssen, A. J. Olsen, and D. Altin. 2014. Multigenerational Exposure to Ocean Acidification during Food Limitation Reveals Consequences for Copepod Scope for Growth and Vital Rates. Environmental Science & Technology **48**:12275-12284.

Peer, A. C. and T. J. Miller. 2014. Climate Change, Migration Phenology, and Fisheries Management Interact with Unanticipated Consequences. North American Journal of Fisheries Management **34**:94-110.

Pikkitch, E., P. D. Boersma, I. L. Boyd, D. O. Conover, P. Cury, T. E. Essington, S. S. Heppell, E. D. Houde, M. Mangel, D. Pauly, E. E. Plaganyi, K. Sainsbury, and R. Steneck. 2012. Little Fish: Big Impacts. Lenfest Ocean Program, Washington, D.C.

Ries, J. B. 2011. Skeletal mineralogy in a high-CO_2 world. Journal of Experimental Marine Biology and Ecology **403**:54-64.

Ries, J. B., A. L. Cohen, and D. C. McCorkle. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. Geology **37**:1131-1134.

Roberts, D. A., S. N. R. Birchenough, C. Lewis, M. B. Sanders, T. Bolam, and D. Sheahan. 2013. Ocean acidification increases the toxicity of contaminated sediments. Global Change Biology **19**:340-351.

Rothschild, B. J., J. S. Ault, P. Goulletquer, and M. Heral. 1994. Decline of the Chesapeake Bay oyster population: a century of habitat destruction and overfishing. Marine Ecology Progress Series **111**:29-39.

Secor, D. H. 1992. Application of otolith microchemistry analysis to investigate anadromy in Chesapeake Bay striped bass *Morone saxatilis*. Fishery Bulletin **90**:798-806.

Simpson, S. D., P. L. Munday, M. L. Wittenrich, R. Manassa, D. L. Dixson, M. Gagliano, and H. Y. Yan. 2011. Ocean acidification erodes crucial auditory behaviour in a marine fish. Biology Letters **7**:917-920.

Tomanek, L., M. J. Zuzow, A. V. Ivanina, E. Beniash, and I. M. Sokolova. 2011. Proteomic response to elevated pCO_2 level in eastern oysters, Crassostrea virginica: evidence for oxidative stress. Journal of Experimental Biology **214**:1836-1844.

Waldbusser, G. G., H. Bergschneider, and M. A. Green. 2010. Size-dependent pH effect on calcification in post-larval hard clam Mercenaria spp. Marine Ecology Progress Series **417**:171-182.

Waldbusser, G. G., R. A. Steenson, and M. A. Green. 2011a. Oyster Shell Dissolution Rates in Estuarine Waters: Effects of Ph and Shell Legacy. Journal of Shellfish Research **30**:659-669.

Waldbusser, G. G., E. P. Voigt, H. Bergschneider, M. A. Green, and R. I. E. Newell. 2011b. Biocalcification in the Eastern Oyster (Crassostrea virginica) in Relation to Long-term Trends in Chesapeake Bay pH. Estuaries and Coasts **34**:221-231.

Waldbusser, G.G., E. N. Powell, and R. Mann. 2013. Ecosystem effects of shell aggregations and cycling in coastal waters: an example of Chesapeake Bay oyster reefs. Ecology 94:895–903.

Waldbusser, G.G., B Hales, CJ Langdon, BA Haley, P Schrader, EL Brunner, M.W. Gray, C.A. Miller, and I. Gimenez. 2014. Nature Climate Change 5.

Walther, K., K. Anger, and H. O. Portner. 2010. Effects of ocean acidification and warming on the larval development of the spider crab Hyas araneus from different latitudes (54 degrees vs. 79 degrees N). Marine Ecology Progress Series **417**:159-170.

Walther, K., F. J. Sartoris, and H. Portner. 2011. Impacts of temperature and acidification on larval calcium incorporation of the spider crab Hyas araneus from different latitudes (54 degrees vs. 79 degrees N). Marine Biology **158**:2043-2053.

Washington State Blue Ribbon Panel on Ocean Acidification. 2012. Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response.*in* W. D. o. Ecology, editor., Olympia, WA.

Wilberg, M. J., M. E. Livings, J. S. Barkman, B. T. Morris, and J. M. Robinson. 2011. Overfishing, disease, habitat loss, and potential extirpation of oysters in upper Chesapeake Bay. Marine Ecology-Progress Series **436**:131-144.