Delaware and Ocean Acidification: Preparing for a Changing Ocean

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EXECUTIVE SUMMARY

The Science of Ocean Acidification

When increasing amounts of carbon dioxide in the atmosphere from human activities dissolves in the ocean, it changes the carbon chemistry, lowering pH. This change is called ocean acidification.

- Ocean Acidification is happening right now and is measurable in the environment.
- Organisms that build shells and skeletons from calcium carbonate (oysters, clams, coral, lobsters, shrimp) might be at special risk.
- Estuaries are under additional acidification pressure from algal growth and decay stimulated by nutrients and debris from runoff and sewage.
- Ocean Acidification interacts with other "stressors," like temperature increase, de-oxygenation and food web changes that together might have additional or opposing effects on species and ecosystem services.

Delaware

- Climate change is already having effects in Delaware, with mean and seasonal temperatures increasing. Forecasted changes to sea level and precipitation will have implications for salinity in the Delaware Bay, with implications for carbon system balance and buffering to acidification.
- Over 70% of Delawareans believe that climate change is real and that the state should take immediate action to address it.
- Delaware's coastal resources are economically important to the state and could be threatened by ocean acidification, especially because greater than 50% of monitored stream segments in the state are already impaired with low dissolved oxygen and elevated nutrients.

Recommendations to Get Started

1.) Form an ocean acidification working group including scientists, resource managers, NGOs, policymakers, citizen groups and industrial partners:
   a. Define a specific set of questions and priorities.
   b. Inventory and improve existing water monitoring.
   c. Invest in targeted research to fill gaps.

2.) Integrate ocean acidification across state policymaking.

3.) Coordinate with other Mid-Atlantic States.

4.) Consider the feasibility of recommendations from Kelly and Caldwell, 2013.

5.) Increase public and policymaker awareness.

INTRODUCTION

Ocean Acidification is changing today's ocean with huge implications for sea-life and humans who depend upon the ocean for food, income, and the production of goods and services. A balanced, healthy ocean is important for the health and wellbeing of all people, but has special relevance for coastal communities and developing countries.

The observed change in global carbonate chemistry occurs because of well-understood processes as increasing amounts of carbon dioxide (CO_2) in the atmosphere dissolve in seawater. This natural process helps regulate atmospheric levels of CO_2, but the unprecedented growth of fossil fuel use by humans is disrupting the balance, causing rapid and extreme changes to ocean chemistry that may result in the extinction of some marine organisms, especially since ocean acidification is taking place in an ocean experiencing temperature changes, reduced dissolved oxygen and increased pollution (NOAA, 2010). Together, these pressures could overwhelm the coping ability of many organisms.

Even if all fossil fuel burning ceased tomorrow, the ocean will experience significant acidification before reaching equilibrium in thousands of years (Archer, 2005). Today's surface waters become tomorrow's bottom waters, separated from the atmosphere for a long time as organic matter is decomposed and acidity increases further, before upwelling to the surface decades from now and bathing sea-life in a chemical mix that may threaten their survival. In fact, the acidic waters upwelling now were in equilibrium with an atmosphere much less saturated with CO_2 than today's atmosphere, so scientists expect the rate of acidification to continue accelerating.

Most of the research in ocean acidification has been conducted in the past decade (Mathis, 2015). Key questions about ecosystem and economic effects are still unanswered. Researchers have been challenged by technological limitations in monitoring sensors, missing baseline data for most coastal areas, and the inherent complexity in measuring the carbonate system and controlling it in experiments (Dickson, 2007). There are now international guides to best practices in acidification research that should make it easier to standardize and compare experimental data, but the field still faces issues with using datasets that were not prepared with this area of study in mind and in devising new research designs to allow for more complete study of the effects on the marine food web (Riebesell, 2010). As the literature has evolved, the list of physical and biological effects of ocean acidification keeps growing.

Although some effects are well-understood, like the threat posed to shellfish in areas subject to strong upwelling, the complexity in measuring and predicting the impacts of decreasing pH has made it difficult for people and governments to judge the appropriate level and types of mitigation and adaptation efforts needed to head off the worst effects. Furthermore, the coastal and estuarine environments that are of special interest to us are extraordinarily complex.

Estuarine chemistry is like a Rubik's Cube. Global temperature change, anthropogenic watershed impacts (land-use change, pollution, nutrient-loading, fishing, and industrial use) and biological activity interact and affect the concentration of elements and the chemical balance in the water. Just like with the toy, controlling one side does not mean that the puzzle is solved. In fact, it can be very easy to solve just one side of the cube, while the others remain hopelessly mixed up. When you try to solve a second side, you cannot maintain the first. The whole puzzle must be addressed at once. Yet, much of water quality policy is aimed at controlling a single variable at a time.

Ocean acidification uniquely challenges government institutions because it is a multi-sector and multidisciplinary threat; urgent, yet information is still coming out; and requires international, national, state, and local government engagement. Since the Federal Ocean Acidification Research and Monitoring Act of 2009 (P.L. 111-11), the U.S. Federal Government has invested in further scientific research and prepared a multi-agency strategic plan intended to direct federal investments and spearhead the U.S. response (Interagency Working Group on Ocean Acidification (IWG-OA), 2014).

Individual states have also taken action, beginning with the state of Washington's Blue Ribbon Commission Report in 2012 and now including reports issued by Maine and Maryland in 2015. Although ocean acidification is a global phenomenon, the experience of the coastal states will be dependent on their own environmental conditions and unique geology and biology. So, there is an opportunity to take steps to minimize damage and protect important resources, even as the country and the world work to address the larger drivers of climate change.

This report is the first step in preparing the State of Delaware for Ocean Acidification. Inside, it summarizes the science, describes Delaware's unique case, discusses current national and state policy initiatives, and makes recommendations for further action both within the state and in regional organizations.

THE SCIENCE OF OCEAN ACIDIFICATION

Introduction to Carbon Chemistry in Seawater

The chemistry of ocean acidification is straightforward and well established. Carbon dioxide gas dissolves in the water and is either used by aquatic plants for photosynthesis or takes several chemical paths, resulting in lower pH and less stability of the carbonate minerals that comprise marine animal shells and skeletons.

The basic equilibrium equation of CO_2 dissolution in the ocean is:

CO_2 (gas) $\leftrightarrow$ CO_2 (aqueous) + H_2O $\leftrightarrow$ H_2CO_3 $\leftrightarrow$ HCO_3^- + H^+ $\leftrightarrow$ CO_3^{2-} + $2H^+$

The concentrations of the products of the reaction and the speed of the various reactions depend on conditions like temperature, pH and the balance of acids and bases already in the water.

When people discuss the carbonate chemistry of seawater, they often refer to several different parameters that describe the state of the system (Zeebe, 2001):

Dissolved inorganic carbon (DIC): DIC is the total bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and aqueous carbon dioxide, the products of the equilibrium equation. It tells you how much carbon dioxide is present in the various forms it takes after reacting with water molecules.

Partial pressure of carbon dioxide (pCO_2): pCO_2 describes the amount of CO_2 present as a dissolved gas.

Total alkalinity (TA): TA is the total of HCO_3^-, CO_3^{2-}, B(OH)-, OH- and sometimes small amounts of other molecules, minus the concentration of protons (written as H^+). Alkalinity is a complex chemical concept, but can be simplified as the amount of bases available to buffer acids. It is a description of the relationship between negatively charged species and positively charged protons.

pH: The amount of protons is described by the concept of pH (the negative logarithm of the total concentration of H^+). So, the more protons there are and the less alkalinity to react with and "buffer" them, the lower the pH of the system. The equilibrium equation of CO_2 dissolution describes how H^+ is produced as HCO_3^- and CO_3^{2-} are formed and this is why the ocean is described as acidifying with increasing atmospheric carbon dioxide.

The relationships between the carbon parameters: DIC, TA, pCO2, and pH are complex. We can use specific knowledge about two parameters to calculate the other two. Selecting which two parameters to measure is not just a logistical issue; it also depends on what you want to know and where you are working. Some researchers will measure all of them, especially in highly variable environments, to improve accuracy.

There are some shorthand rules to understanding the relationships between the parameters:

1.) Photosynthesis decreases DIC (by consuming CO_2) and increases pH.
2.) Respiration from degradation or consumption of organic matter increases DIC (because CO_2 is released, much like how we exhale CO_2 during our digestion).
3.) Alkalinity does not change with the dissolution of CO_2. This conservative property allows us to tell the difference between changes in carbon parameters that are related to the mixing of fresh and saltwater masses and those caused by chemical and biological processes.

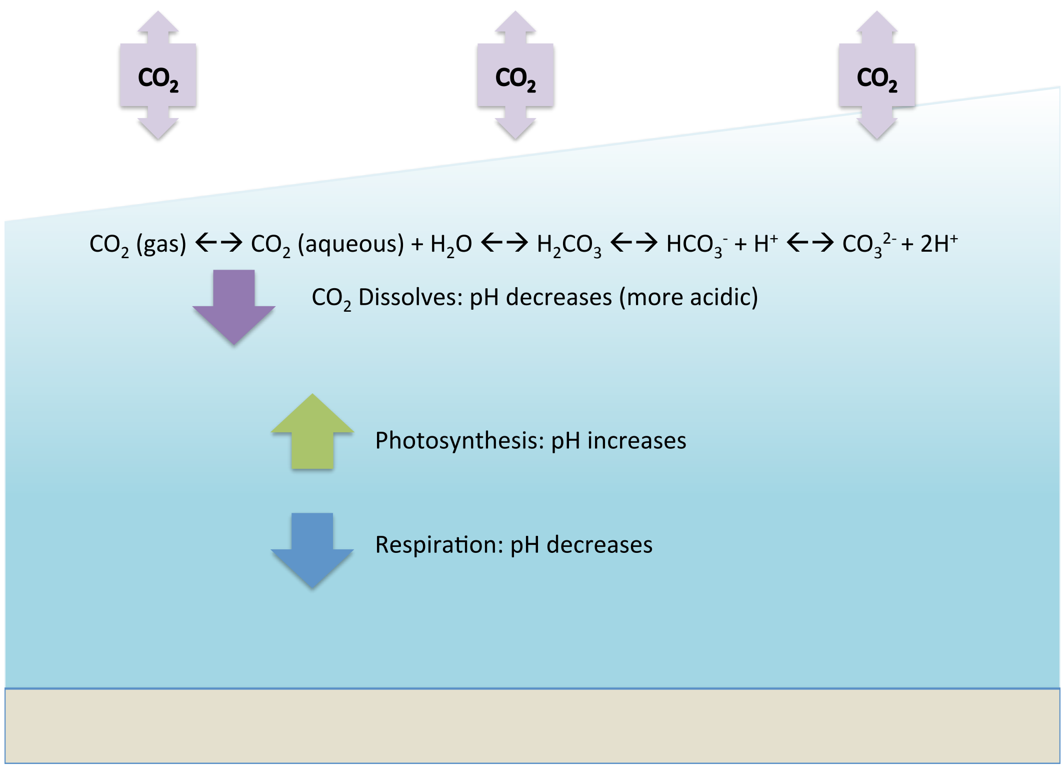

Figure 1: Major oceanic drivers of pH change.

Discussions of ocean acidification often include a discussion of carbonate saturation states (represented by Ω). Because CO_2 chemistry is complex and variable and people are often interested in the effects of carbon system change on organisms, particularly organisms that use carbonate minerals to form shells, we describe the equilibrium in terms of its ability to sustain those minerals without dissolving them. Super-saturation, $\Omega>1$ is favorable for making shells and skeletons. When organisms make calcium carbonate ($CaCO_3$), they reduce alkalinity, because they take CO_3^{2-} out of the water. A particularly useful concept is the idea of "carbonate weather (Waldbusser, 2014)." Organisms at the coasts and in estuaries are subject to highly variable carbon chemistry over different time cycles. In order to understand the effects on their health, it is necessary to know how the "weather" lines up with their life stages. It is also important to know the frequency and magnitude of their exposure to changes (Waldbusser, 2014).

Depending on the balance of the system, building shells and skeletons can be energetically easier or harder to do. Shells formed under difficult conditions are often deformed or weak, affecting their use as protection. Some organisms can manipulate the chemistry of the water as they form their skeletons, but there is an energy cost to this process (Reinfelder, 2011). Once the shells and skeletons are formed, changes in carbon chemistry (under-saturation, $\Omega<1$) can cause them to dissolve, which means the organism has to work harder to maintain them and possibly will be more likely to die, especially in vulnerable life stages. The dissolution of calcium carbonates would cause alkalinity to rise, buffering the system against further pH change. In fact, the major source of alkalinity in freshwater is chemical weathering of rock. Freshwater is more acidic than seawater.

The Global Scale

Since industrialization, there has been a total anthropogenic release of CO_2 of more than 9 Pg, ~ 85% from industrial processes (engines, factories) and ~ 15% from land use changes, like deforestation and removal of wetlands (Mathis, 2015). The oceans are absorbing at least a quarter of the additional CO_2 being added to the atmosphere by humans (Sabine, 2004 and 2010; Le Quéré, 2014) and have already experienced a 30% increase in acidity since industrialization (Dore, 2009; IPCC, 2013). Current predictions suggest a 0.3 pH decline by the end of this century, a rate that is increasing with time (IPCC, 2013). pH is measured on a logarithmic scale, meaning a pH decline of, for example, 8.0 to 7.9 is a tenfold change.

A study of seven, independent, long-term datasets from open ocean sites around the globe provides further evidence of these changes to the carbon system (Bates, 2014). Ocean acidification is not a potential problem. It is already happening in the environment. The sources and sinks of alkalinity are no longer in balance (Hönisch, 2012).

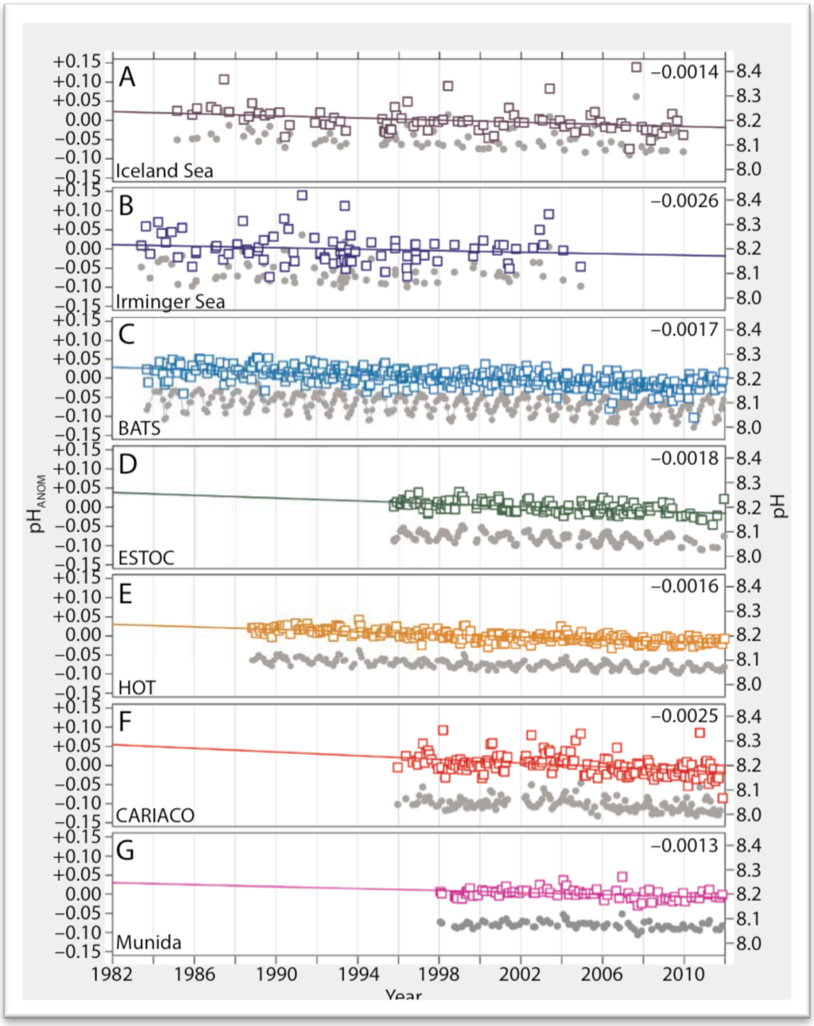

Figure 2: pH trends at 7 open ocean sites (from Bates, 2014).

Ocean acidification has serious global ramifications. Although there have been acidification events in the fossil record, modern ocean acidification is occurring at an unprecedented rate. The closest analog to modern ocean acidification, the Paleocene-Eocene Thermal Maximum (PETM), despite a much slower pace, resulted in a massive aquatic extinction event (Doney, 2009).

The greatest change is projected in the biologically productive tropics, but the Polar Regions will be corrosive to carbonates first (NOAA, 2013). Scientists have found that the problem is already acute at the North Pole, where a combination of warming temperatures, increased respiration of organic matter, low pH freshwater influx from melting ice and increased river discharge are exacerbating the trend and dramatically decreasing the stability of carbonates (Mathis, 2015).

Effects on Sea-life

Beyond the impacts on calcifying organisms like coral, crabs, oysters and shrimp, we are learning that the chemical alterations to the water can affect larval survival of many organisms, change behavior, and affect where organisms can live and which organisms can compete. Photosynthesis, respiration, nutrient acquisition, behavior, growth, reproduction and survival are all potentially affected (Gattuso, 2011). Studies have demonstrated changes in olfactory and neurotransmitter action in marine fish (Simpson, 2011; Nilsson, 2012). Even organisms that do not die in acidifying conditions may pay the price in increased metabolic costs to regulate the pH of body fluids (Gattuso, 2011). Increased energy costs could reduce growth, productivity and/or survivability.

Photosynthesis in the oceans generates oxygen that we breathe and fuels the entire food chain. There is potential for changes to the rates of the photosynthetic reactions due to increased pCO_2 and lower pH, but it is difficult to predict because of carbon concentrating mechanisms that some organisms use to control their internal chemistry and because of mixed experimental results. Although some have suggested that additional CO_2

would increase photosynthesis, accompanying changes to water chemistry from ocean acidification and other environmental stressors related to climate change could negate the effect (Mackey, 2015).

Many studies have been done to see the direct effects of changing pH and carbon parameters on single species at different life stages, but the picture becomes more complex when you consider the linkages between species and whole ecosystems. There will be new "winners" like purple sea urchins (Pespeni, 2013) and some sea grasses and algae (Kroeker, 2010) and new "losers," changing the composition of marine communities. As conditions change, there could be location and reproductive timing shifts that decouple predators and their prey (Breitburg, 2015).

Furthermore, we do not yet understand the limits on acclimation, when an organism adjusts to changing conditions, and adaptation, the genetic response of a species to changing conditions. It is an important first step to directly test changing chemistry on key species, but next we must test more natural conditions and increase collaborative efforts between lab and field teams to better simulate future conditions in more complex environments with all of the organisms present in the ecosystem (Andersson, 2015).

Effects on Nutrients, Metals and Physical Processes

In the ocean, physics, chemistry, and biology interact and affect one another. When the chemical system is changing because of ocean acidification, the effects aren't just limited to living creatures. The speciation of metals, an important factor in toxicity and bioavailability, is sensitive to pH. That could mean toxic metals are freed to poison sea-life or beneficial metals needed for growth are suddenly inaccessible. Additionally, the way that waste particles absorb metals and aggregate, processes that control the location and movement of both pollutants and nutrients are potentially affected by acidification (Millero, 2009). Aggregation processes are also important to the ocean's biological pump, through which surface organic carbon is moved into the deep ocean and sequestered, effectively removing carbon dioxide from circulation in Earth's atmosphere. The effectiveness of the pump depends on the ability of tiny particles to adhere to one another and sink out of reach of organisms that would digest them. Even physical conditions like the way sound travels and how and whether water masses mix can be affected by changing chemistry. So, it will be important to study the full water column, from beneath the sediment to the interface with the atmosphere, in both open ocean and coastal locations.

Coasts and Estuaries

Although ocean acidification is a global problem, research suggests that different localities will experience its impacts in different ways due to their unique geological, environmental, economic, and cultural characteristics. The open ocean is relatively uniform, stable, and predictable when compared to coasts and estuaries. It is like a desert in terms of the amount of space and scarcity of life. Coasts and estuaries are a more difficult carbon study, because of the intensity of human activity and wide natural variation in physics, chemistry and biology across time and space. To tease out the underlying trends, we need more measurements in more places at more times. In many critical habitats and important fisheries, we do not currently have a very good idea of what the baseline carbon system conditions and usual variances are, which makes it tough to define changes and attribute them to a cause. Though open ocean acidification is dominated by anthropogenic carbon emissions, acidification in estuaries and at the coast is also driven by nutrient-fueled respiration and modified by temperature change, de-oxygenation, and food web changes.

Near-shore waters are experiencing dramatic changes driven by many causes: temperature increase, decreasing dissolved oxygen, and acidification, which together can result in a more dramatic change than any one of the factors alone (Cai, 2011; Sunda, 2012). Emissions from shipping traffic can also cause regional pH reductions (Hassellöv, 2013). There is increased freshwater input from rivers and groundwater due to more frequent and intense storm events. Nutrients are also increasing, both by material washed in by storms, because of the removal of trapping areas like marshes, or directly from human inputs of sewage, trash, and agricultural runoff, rich in nitrogen. When these waters are enriched with extra nutrients like nitrogen and phosphorus, a process we call eutrophication, explosions of algal growth can occur, taking advantage of the extra fuel. Although this may result in a temporary drawdown of atmospheric CO_2 and consumes the extra nutrients, eventually ending the bloom, when the organisms all die off, most are decomposed, releasing the CO_2 again and using up water column oxygen. The end result is a water mass where oxygen is low (hypoxia) or absent (anoxia) and pH is low, especially if the water mass isn't mixing and ventilating because of salinity-driven density differences, like you would find in the summertime in many estuaries (Rabalais, 2014). These conditions are fatal for many fish and other organisms, and can drive migrating species to other locations. The causes and effects of these stressors are linked to carbon system change and it is important to remember that they act together on the ecosystem. With each additional stressor, the probability of any one causing critical damage to physiological or ecological processes increases (Breitburg, 2015).

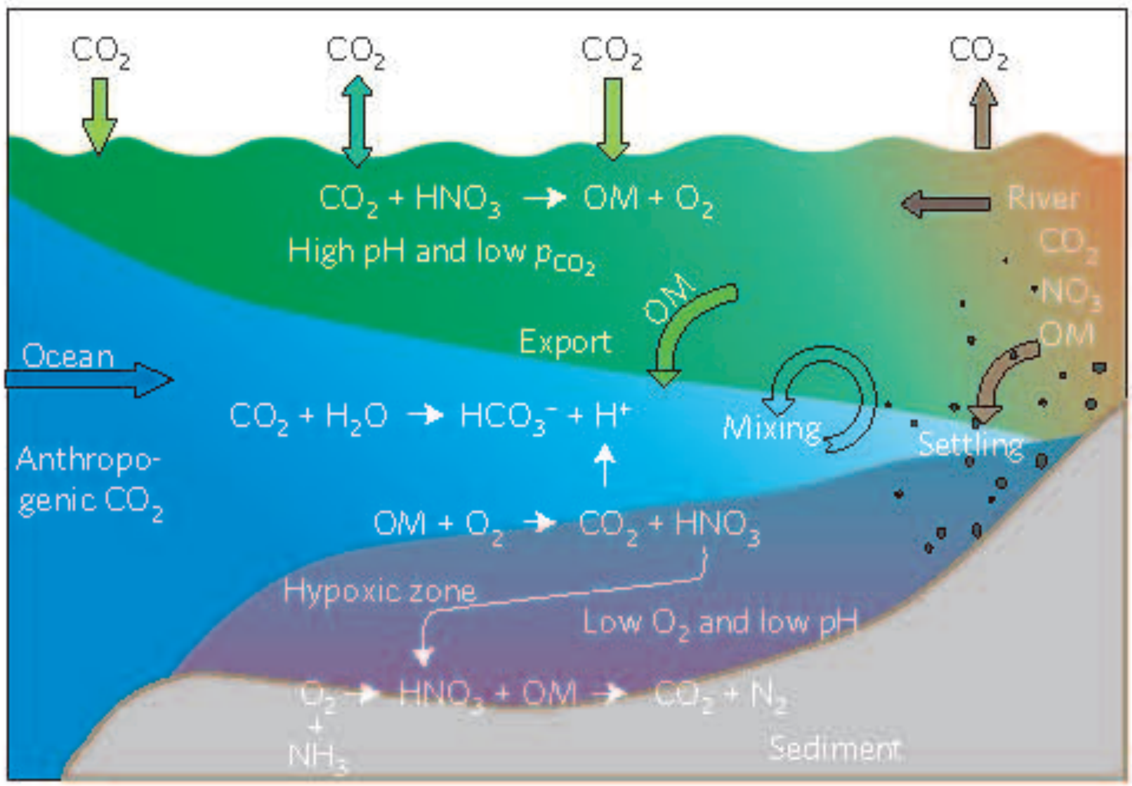

Figure 3: The complex carbon chemistry interactions in estuarine waters (Cai, 2011).

Multiple stressors in estuaries and on our coasts can have additive effects, cancel each other out, or even create additional damage above and beyond their effects alone. For example, scientists anticipate an average increase of about 2.7 degrees this century in the sea surface temperature, under a "business as usual" emissions scenario (Bopp, 2013). By itself, temperature change will alter biological community composition and total production, but increased temperature can also cause increased sensitivity to rising pCO_2

(Kroeker, 2013). The scientific community is working to address this idea by designing more experiments reflecting all of the co-occurring changes to the future ocean.

Near-shore waters are also an important part of the total global carbon budget. Although coasts and estuaries make up only a tiny fraction, 7.5%, of the ocean's surface area, they are an important link for carbon movement, or "flux," between the land, open ocean and atmosphere at about 17% of the total ocean uptake of CO_2 (Cai, 2011). Some of these areas are called "sinks," where CO_2 is dissolved into the water. Others are called "sources," which release CO_2 into the atmosphere. The difference depends on the amount of productivity and respiration/decomposition in the water. The carbon system changes from ocean acidification may shift areas from sinks to sources or vice versa. We depend on the ocean to reduce the effects of carbon emissions in the atmosphere. If it becomes less able to do so, climate change in the atmosphere could be more dramatic. Right now, the high atmospheric levels of CO_2 favor dissolution in most places, raising pCO_2 in the water. Some estuaries are experiencing less dramatic effects from these changes because they are currently sources of CO_2, but pCO_2 in those waters may also increase in the future because of less outgassing (Phillips, 2015).

DELAWARE

Delaware and Climate Change

Delaware has 381 miles of shoreline and any point in the state of Delaware is just 8 miles or less from tidal waters, making it one of the country's most truly coastal states

(Latham, 2012). There are 10 major aquifers in Delaware, 2,500 miles of rivers and streams, 3,000 acres of ponds and lakes, and 25% of the land mass is freshwater or saltwater wetlands. The Delaware Bay is home to more than 200 resident and migrant aquatic species and is the largest spring staging area for migratory shorebirds in Eastern North America. Over 1 million birds use our state's habitats each year and some even nest here. Delaware's famous beaches draw about 5 million visitors each year (DNREC Division of Climate and Energy, 2014). So, what happens to the ocean, the Delaware Bay, and the Chesapeake Bay is going to affect life in all of our state's communities.

In fact, over 70% of Delawareans believe climate change is happening and we should act immediately to reduce the threat to our state. Ocean acidification, although lesser known than climate change and sea level rise to most members of the public, has the same root cause as climate change, greenhouse gas emissions, and is further exacerbated by climate change's temperature effects. Since a majority of Delaware's citizens believe that both collective and personal efforts can help reduce climate change and that there are many things that can be done, the time is ripe for the state to consider its own role in working alongside the public to improve the future of our state's waters. (Responsive Management, 2014).

When 53% of Delawareans in the survey of "Delaware Residents' Opinions on Climate Change and Sea Level Rise (Responsive Management, 2014)" say they are experiencing the effects of climate change, they are absolutely correct. According to the Delaware Climate Change Impact Assessment (DNREC Division of Energy and Climate, 2014), the statewide mean annual and season temperatures are up 2 degrees over the past century, or 0.2 degrees per decade. Although it sounds like a small number, these average changes can be very meaningful, especially in terms of rising minimum temperatures, both for sea-level rise and for agricultural productivity. Rising temperatures also cause more frequent extreme events, with the ability to cause severe damage to communities in the short-term. In contrast with other East Coast states, the report found no significant changes in precipitation in Delaware over the past century, except during the fall, where there was an average increase of 2.7 inches, 0.27 inches per decade. However, precipitation is expected to increase in the state by 10% by 2100, with more frequent rainfall extremes (DNREC Division of Energy and Climate, 2014).

Climate Change and The Delaware Estuary

Think of the Delaware Bay like a mixing bowl, with freshwater and groundwater flowing in and seawater coming in and out with the tide. Along the bay, salinity goes from zero to the 30 and greater values found in the open ocean. At the lowest salinity, the water is very similar to river water, and at the mouth of the bay, it is coastal ocean water. The mid-salinities are extremely important zones, home to massive biological activity, nurseries for sea-life, factories for the packaging and movement of sediment and nutrients, and controls of how much carbon is fed to the ocean for further biological activity and for sequestration in the seabed. There are regular chemical, physical, and biological fluctuations over each day, each tidal cycle, and season. Life in the Bay is adapted to cope with these changes and time their development according to environmental conditions for the best possible chance of success. But when there are long-term changes to the balance, we must also expect changes in the ecosystem and its inhabitants.

The extra precipitation forecasted in the climate report will change the water chemistry (Gledhill, 2015). Freshwater is more acidic than seawater and is less buffered against pH change. It also carries more land-derived organic matter, waste, debris and fertilizer, which can fuel algal blooms that further reduce pH when the blooms fade and are decomposed. The intruding seawater expected by sea-level rise projections could perhaps balance some of the increased freshwater, since seawater is normally well-buffered against chemical change, however, this is the same seawater experiencing ocean acidification, so it is less able to provide such protection. And the salinity itself can be a shock to the system, killing or driving off plants and animals that are not well suited to high concentrations of saltwater. Delaware already experiences 10-35 significant coastal storms annually, with the potential for serious flooding (Delaware Sea Grant, 2015).

These climate change-caused water quality changes affect our communities, too. When the temperatures increase, there is more demand for irrigation. With increased flooding, pollutants can be mixed into sensitive areas and saltwater can poison freshwater ecosystems. Flooding can affect human healt: there is a correlation between increased sea surface temperature and bacterial growth and as our infrastructure is taxed by floodwaters, contaminated water can get into drinking water. Poor quality water also affects business, as water needed for industrial processes, like energy production, becomes more difficult and expensive to obtain. At the same time, the state is projecting further population growth, an additional pressure on our water resources (DNREC Division of Energy and Climate, 2014).

Connecting The Dots: Multiple Stressors and Delaware's Water Quality History

Just as you cannot consider the Delaware River separately from the Bay or from the groundwater that drains into it, it is not enough to consider ocean acidification alone. The science tells us that multiple stressors will interact with increasing acidity, with uncertain ecological outcomes. But, our region has a proud history of success in environmental policy and coping with complex water quality challenges.

After over a century of the Delaware River and Watershed being among the most foully polluted in the United States, decimating local wildlife and all but destroying the local fishing industry, Delaware, New Jersey, New York, and Pennsylvania came together to form the Delaware River Basin Commission, the first federal and state watershed compact, which made history with the first load allocations on discharges to our waterways. Using the further authority of the Clean Water Act, the states were able to make huge strides in water quality improvement and see the return of fish and birds, with the economic value of the renewed recreational fishery estimated at $25 million per year. The recovery continues today, with a juvenile Sturgeon caught in Wilmington, DE for the first time in 50 years and Bald Eagles returning to Philadelphia to nest (Kauffman, 2010).

The evidence of improvement is also clear in long-term records of water chemistry collected over 30 years (Sharp, 2010). Better sewage processing reduced inputs of nitrogen and phosphorus from urban environments, raising oxygen levels in the water. The study showed that not all of the hypoxia was the result of eutrophication-driven algal blooms, though. Sharp cautioned that there is a "tendency to oversimplify and associate all aquatic hypoxia with algal response to nutrient enrichment." Defining the drivers of the problem accurately was key to responding effectively. This is why it is important to have both a baseline of conditions in the waterways and also to undertake detailed study in order to separate out the various causes contributing to chemical trends.

Ocean Acidification As An Economic Threat to the Value of Delaware's Water Resources

Delaware's water resources are critically important to the regions' people and industries. There are eight million Americans living in the Delaware Watershed and 15 million, 5% of the U.S. population, depend on it for drinking water. The Delaware River supports the largest freshwater port in the world, with over $19 billion in economic activity (Kauffman, 2010). Water resources and habitats in the Delaware Estuary and Watershed are worth over $10 billion to Delaware, New Jersey and Pennsylvania, including 500,000 jobs, making it one of the "nation's most valuable tidal river systems." These numbers do not include the jobs and wages of companies that rely on the water for industrial and commercial processes. (Kauffman, 2011)

Beyond the direct use of water as a commodity, the watershed's environment provides "ecosystem services," including climate regulation, water purification, flood control and recreational opportunities. The ecosystem goods and services are valued at $12 billion annually in 2010 dollars, with a net present value of $392 billion, calculated over a hundred year period. Note that these economic studies are unable to capture ancillary benefits, like tax receipts beyond the port or the value provided by organisms, like mussels, to water filtering. Although other states in the region have larger fisheries, Delaware's commercial landings in 2010 totaled $34 million. More significant is the state's recreational fishery, with hunting, fishing, and animal watching worth $134 million in 2006 dollars in the state of Delaware alone (Kauffman, 2011). An economic valuation of wetland ecosystem services in Delaware found that despite the difficultly with quantifying the full value of wetlands, it could be demonstrated that a 1.2% decline in wetlands over 15 years was responsible for a loss of a minimum of $2.4 million dollars (Industrial Economics, 2011).

Delaware's influence goes beyond the Delaware River and Bay. Thirty-five percent of Delaware's landmass drains into the Chesapeake Bay. The Delaware portion of the socioeconomic value of that watershed is worth $2 billion in annual economic activity from services like water supply and water quality services; ecotourism and recreation; and agriculture. The Chesapeake is responsible for 12,800 Delawarean jobs (Kauffman, 2011).

Beyond the fresh and brackish water resources, Delaware also benefits from its connection to the Atlantic Ocean, a powerful economic multiplier that adds $6.9 billion to the state's industrial production; 59,000 jobs; and $711 million in taxes. These figures, taken from the 2012 Delaware Sea Grant report on the "Contribution of the Coastal Economy to the State of Delaware, " only include the four oceanfront zip codes and a small amount of spillover activity in neighboring zip codes, making them a low bound of the total estimated value (Latham, 2012). For example, Sea Watch International, the world's largest harvester and processor of clam products, has a processing plant in Milford, DE. This ocean economy is comparable to the agricultural economy in Delaware, but importantly is much more labor intensive, providing twice as many jobs to the state. Although many assume that these jobs are largely seasonal and temporary, long-term, all-season jobs are approximately 2/3 of the total (Latham, 2012).

Delaware's Water Future

These valuable water resources are under threat. In almost all of Delaware's watersheds, greater than 50% of monitored stream segments are classified as impaired, with a majority showing low oxygen, elevated nutrients, and increased bacterial levels, all of which can contribute to increased acidity both in the rivers and when they meet the bays and ocean (DNREC Division of Energy and Climate, 2014).

At the same time, University of Delaware researchers are making strides in fully characterizing both the carbon system in the Delaware Estuary and its productivity (Joesoef, 2015). This information is essential to defining what is "normal," modeling what may happen in the future, and directing policy interventions aimed at reducing local impacts of global climate change and ocean acidification. With the state taking action on shellfish aquaculture in the Inland Bays, such information will also be economically important.

The recently released Climate Framework for Delaware (DNREC, 2014) sets out an ambitious agenda to address climate change impacts in the state. It focuses efforts on mitigation, through a reduction in emissions; resilience and adaptation to expected increases in temperature, precipitation and sea level; and flood avoidance. The mitigation efforts aimed at climate change will also assist with ocean acidification, by reducing the amount of CO_2 and other emissions that dissolve or deposit in our waterways and ocean.

POLICY

National Ocean Acidification Policy

As recently as 2013, the National Academy of Sciences reported that fewer than 10% of Americans are aware of the process of ocean acidification or its known and potential impacts. At the same time, a survey of the world's top ocean acidification scientists found remarkable agreement on the facts that acidification is a serious, human-caused problem, observable now in the environment and expected to degrade the oceans (Gattuso, 2013). Because of that gap between the seriousness of the issue and public understanding, many have worked on educating the public and policymakers about their concerns over the past few years, especially the West Coast shellfish industry, which experienced an acidification-related die-off of their larval populations in 2007.

The cornerstone of federal ocean acidification policy is the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM, P.L. 111-11). FOARAM called for the formation of a "comprehensive, interagency plan;" provided for research and monitoring (NOAA, NSF, NASA); directed agencies to assess ecosystem and economic impacts; ordered agencies to develop adaptation strategies and techniques for conservation; authorized four years of spending for NOAA and NASA (ending in FY2013); and generated many reports intended to focus the federal government's work on ocean acidification. It is currently being considered for reauthorization in Congress.

FOARAM led to the formation of an Interagency Working Group on Ocean Acidification that drafted a strategic plan for addressing ocean acidification (IWG-OA, 2014). The plan was later reviewed by the National Academy of Sciences (NRC, 2013). Major themes from the plan include: monitoring ocean chemistry and biological impacts; understanding biological responses to ocean acidification; modeling to predict changes and ecosystem/organism effects; technology development and standardization of measurements; assessment of socioeconomic impacts and development of conservation strategies; education and outreach; and data management and integration. The focus to date has been on concentrating research attention around the issue and the highest priority questions and technology needs. There are also several earlier federal reports on scientific priorities in the area of ocean acidification that have informed federal efforts (NOAA, 2010; NRC, 2010). Appropriators have provided funds for ocean acidification research, but general budgetary strain over the past few years has limited investments.

On the regulatory side, ocean acidification generally falls under the authority of the Clean Water Act (CWA, P.L. 92-500). The CWA has been a powerful tool to improve the country's water quality, but it was designed for addressing point-source pollutants and contaminants. It requires policymakers to determine "natural levels" of the target pollutant and to attribute changes in water quality to a specific source, both of which are tough or impossible tests for the diffuse carbon imbalance that is associated with ocean acidification, even if we could easily identify the threshold level for harm to organisms (Boehm, 2015). Even where regulators have tried to apply CWA to address acidification, they have been confronted by a lack of baseline data, an inability to specifically identify sources within their jurisdiction, and the fact that existing water quality standards do not capture the impairments that are associated with ocean acidification (Cooley, 2015). In fact, there was a lawsuit brought by the Center for Biological Diversity against the U.S.

Environmental Protection Agency (EPA) alleging the agency had failed to regulate this issue. In the end, the courts sided with the EPA, and it is continuing to examine how to use pH and/or saturation state to define a point at which a water body becomes impaired and a threat to sea-life and natural resources.

Even as the government works to create an effective regime to address pH change, marine science tells us that it is not possible to address ocean acidification in a vacuum. Coastal and estuarine waters, home to much of the world's aquatic productivity and human population, are dynamic and under a variety of stressors. Each place has a unique footprint of inputs, physical characteristics and human uses that require policies tailored to their unique challenges. When water quality is generally improved, as it has been over the last century in the Delaware River Basin, we see a system rebound, natural resources return, and increased flexibility to weather extreme events and global trends. Ocean Acidification, driven by carbon emissions, is a global problem in need of global solutions, but the way that our region experiences the changes is potentially in our own hands. "Reduction of global atmospheric CO_2 inputs is the appropriate management focus for decreasing OA, but there are also many management decisions made at regional to local spatial scales that can lessen the exposure to or limit the effects of atmospheric CO_2 (Boehm, 2015)."

When a cancer patient faces treatment, we know that the ultimate cause, the cancer, must be directly addressed, but the doctors also develop a plan to put the patient in the best possible condition to endure the disease and its effects by improving their nutrition, their strength, by reducing stress-related inflammation, and by encouraging them to get mentally strong with friends and family at their side. This is exactly what regions and states can do to prepare for global change. We call it mitigation, the effort to prepare for and adjust to a changing environment in order to reduce the severity of impacts as much as possible.

Ocean Acidification at the State Level

In "10 Ways States Can Combat Ocean Acidification," Kelly and Caldwell argue that states can use existing legal authority to implement policies with the power to make improvements on local drivers of acidification, even while they support larger regional and national efforts. They recommend reducing point source and nonpoint sources of emissions and pollution; reducing erosion and improving storm-water management; developing criteria related to the carbon system (pH, saturation state) based upon local conditions; and adding and protecting resources that filter and buffer water quality against chemical change, like wetlands, bivalves etc. (Kelly, 2013). In fact, some states have begun to address ocean acidification in their territorial waters and regions, even in the absence of direction from the Federal Government.

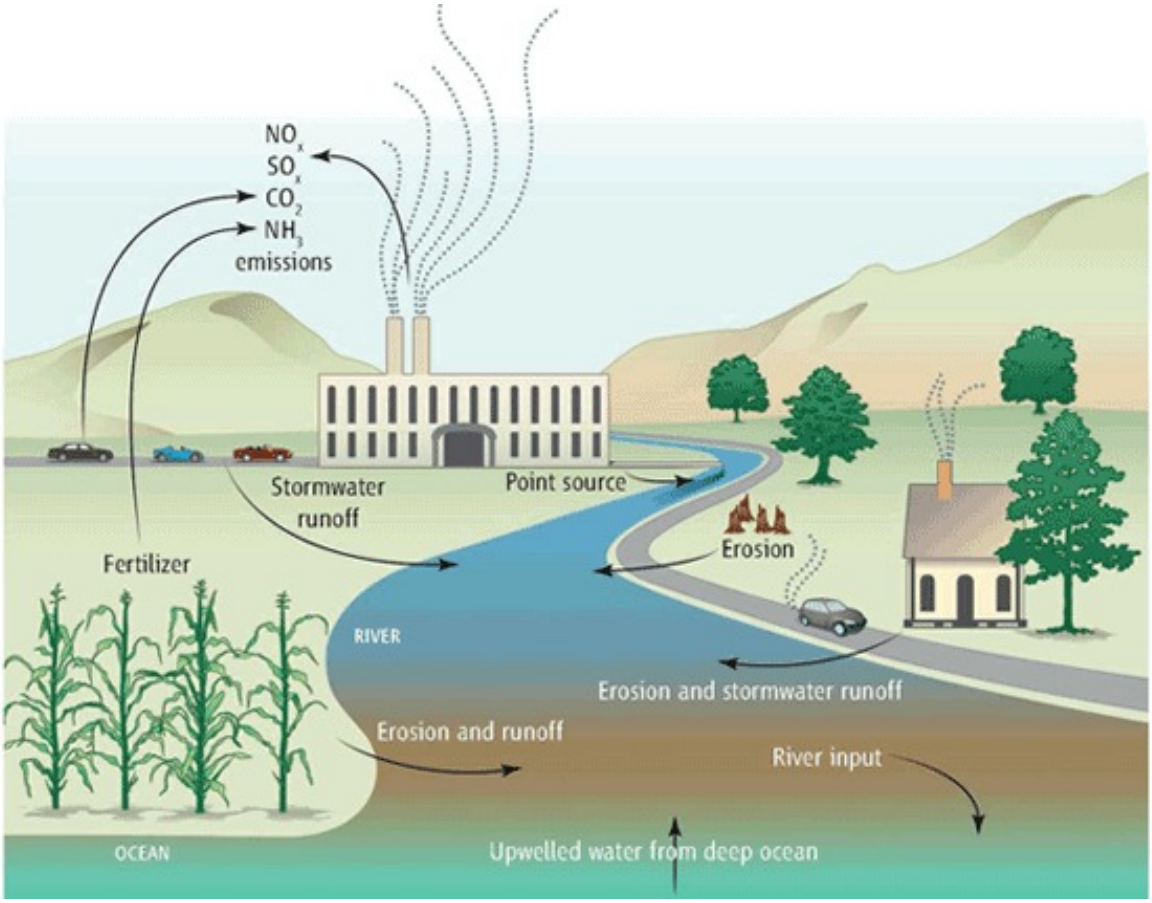

Figure 4: Other sources of acidity to coastal waters (Kelly, 2013).

State action on ocean acidification began with Washington, where shellfish growers were among the first to experience economic effects of changes to ocean carbon chemistry. Legislators created a Blue Ribbon Commission, which issued twin reports: one on the local science (Feely, 2012) and one creating an agenda for state action (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). They recommended a set of policies for the legislature, including: reduction of emissions; reduction of land-use contributions; increasing the industry's ability to adapt to and remediate acidification impacts; increasing research and monitoring in state waterways; informing and educating stakeholders, the public and decision-makers; and planning sustained, coordinated action across the government and industry. Other states have since released their own reports, some from legislative commissions and others through specific agencies with expertise in the area. Maine and Maryland's reports (Maine, 2015; Maryland, 2015) share many of the Washington recommendations like increasing local research and monitoring and assessing the risk to sensitive stocks and key habitats. These states have also worked to build coalitions of public and private groups that can work together to set priorities and adjust plans as more information is gathered and better predictions are made. These inter- and intrastate collaborations are perhaps the most important outgrowth of state reports on ocean acidification, making it possible to integrate the issue with a wide variety of local policies, to give policymakers direct access to the needs and experiences of the people most affected by acidification and other ocean stressors, and to raise the profile of this important issue in advance of crises, in the hope that collective action will give them the best chance at mitigating effects where possible.

RECOMMENDATIONS

1.) Bring Together Delaware's Scientists, Resource Managers, Industries and Policymakers to Address Ocean Acidification in the Context of A Changing Ocean

Form An Ocean Acidification Working Group

Create a working group of policymakers, agency officials, industry representatives, scientists, citizen groups etc. to guide the state's mitigation and adaptation strategies.

Analysts have found that it is, "essential to actively engage all of the relevant stakeholder groups from the outset (Alin, 2015)." Decision-makers should include all those whose responsibilities have implications for acidification: water quality managers with responsibility for setting local discharges; living resource managers that make decisions about fisheries and habitat protection; coastal zone land use managers that make siting and restoration determinations; air quality officials; and coastal resource users, both public and private (Boehm, 2015).

Define a Specific Set of Questions and Priorities

Examples from other states have shown that, "decisions concerning ocean acidification have been made most naturally and easily where information needs were clearly defined and closely aligned with scientific outputs and initiatives (Cooley, 2015)." The working group's primary job will be to figure out the particular questions of interest to the state (key species, habitats, resources etc.), in consultation with a variety of technical and scientific specialists that can provide answers from the literature and suggest how unanswered questions could be investigated.

Improving information flow and coordination between groups working on ocean acidification from the research, monitoring and adaptation angles will help maximize resources around the most critical questions. To get started, two meetings should be planned: a scoping meeting of interested parties to raise an initial set of priorities and questions for the committee's consideration; and a meeting of scientists who work in Delaware's waters to define a set of priorities and gaps in the existing research.

Assess and Improve Existing Water Monitoring in Delaware

There are many private and public entities at all levels of government collecting data in state waters. It is important that the working group first compile an exhaustive inventory of the available data sources and information about how the data is collected. This will allow the group to set priorities in missing areas, and to provide for the improvement of sampling techniques and equipment where necessary so that the information is useful for monitoring acidification and other co-stressors.

Technical experts should also be involved in evaluating the quality of the available data. It is clear that pH measurements alone are not sufficient to understand or predict the effects of changing carbon chemistry on organisms (Barton, 2015; Waldbusser, 2013 & 2015). It is also well understood that the carbon parameters must be measured with high precision to determine the saturation state of minerals within the necessary 0.2% accuracy (Martz, 2015). The University of Delaware has scientists who are determining carbon system parameters in the Delaware Bay and other locations with the required accuracy (Yoesoef, 2015), but it must be determined where such data is missing and how to improve the measurements made by all groups.

The goal should be to produce an "integrated, interdisciplinary biogeochemical and ecological observing network capable of robustly detecting and attributing changes in ocean chemistry to changes in indicators of ecosystem condition and human well-being (Alin, 2015)." Specific tasks would include: establishing spatial patterns and the magnitude of variability, detecting long-term changes, attributing ecological responses to changes and identifying vulnerabilities, facilitating projection of future conditions, and evaluating and improving models in a continuous process as new data is collected (Boehm, 2015). For example, in the Atlantic, researchers have been able to use time-series data from an autonomous mooring to observe pCO_2 changes and separate out different influences (Reimer, 2015).

Most importantly, effective modeling based on well-designed, high-quality investments in monitoring can facilitate easier long-term monitoring and planning at significantly less difficulty and expense. For example, in the Pacific Northwest, 5 years of data collection on carbon system parameters have allowed them to now use salinity, easily and cheaply measured, as a proxy for alkalinity, allowing them to predict the accessibility of carbonates for shells (Barton, 2015).

A variety of monitoring platforms and effort (high/low frequency, fixed, different spatial scales) are needed to cover the resources. Coordinated planning to maximize field efforts will also have the advantage of facilitating data sharing and linking events and inputs across time and space gaps in small projects (McLaughlin, 2015).

2.) Invest in Targeted Ocean Acidification Research

<u>Fill Research Gaps</u>

Once the working group has defined the most important questions and priorities facing Delaware, it will be necessary for the state to fund research that focuses on our local environment and key species, like horseshoe crabs or clams. Some research covering the chosen topics may be already funded by federal science agencies or foundations, in which case the state can try to work to leverage and sustain those existing investments.

An example of priority-setting can be found in the Northeast Coastal Acidification Network, which has identified the following specific research priorities: commercially-important species; multistressor, multiple life stage and multigenerational experiments; ocean acidification effects on local food web interactions; variable pCO2 and process investigations to expose carbonate saturation dynamics; climate quality monitoring; long-term carbonate trends (hind-casting, forecasting, projecting); and mesocosm experiments in the field (Gledhill, 2015). Other similar regional groups, like the West Coast Ocean Acidification and Hypoxia Panel have also identified specific, locally driven information gaps.

3.) Integrate Ocean Acidification Across State Policymaking

<u>Include Ocean Acidification in All Related State Policy</u>

In order to maintain a focused and effective effort around ocean acidification that takes into account the complex interactions between multiple stressors, it will be important for the State of Delaware to consider ocean acidification impacts in other policy areas besides water quality. The "key to managing multiple stressors is to identify underlying commonalities in solutions to address more than one stressor simultaneously," as in the case of low oxygen and acidification both being related to nutrient loading (Breitburg, 2015), land-use, and storm-water treatment.

State interventions have been most successful when work on ocean acidification is fit into existing environmental policies on land-use, climate, and air quality (Cooley, 2015). The diversity of the proposed working group will be an asset in incorporating ocean acidification into other ongoing efforts across state agencies, but leadership will be needed to ensure that all agencies are considering the problem in their planning. Existing efforts to improve air and water quality assist with mitigation of acidification and officials should note the additional benefits of such policies.

4.) Coordinate With Mid-Atlantic States

Just as the Mid-Atlantic led the country last century in regional watershed partnerships, recognizing that the Delaware River was a shared asset and that each state's policy contributed to its water quality, the State of Delaware must lead an effort for increased coordination on ocean acidification science and policy at the regional level. The agenda of tasks for the working group will have analogs at the regional level. Delaware should share information, support coordination efforts by the Mid-Atlantic Regional Ocean Council's (MARCO) and others, provide information about the state's research and monitoring priorities, and encourage the other states to form their own coalitions to address ocean acidification in their own waters by sharing lessons learned.

As much as possible, the State should align policies and regulations with neighboring states to support water quality and natural resources outside of our borders. For example, in 2014, the Delaware River Basin Commission updated pH criteria across the interstate tidal and non-tidal portions of the Delaware River to minimize inconsistency across the states and with the EPA, making it easier to manage this critical resource. Delaware feels the effects of upriver states' actions, but we also affect others, with a large portion of the state draining into the Chesapeake Bay.

5.) Consider the feasibility of the "10 Ways" Regulatory Recommendations

Kelly and Caldwell provided states with a number of regulatory options that rely upon existing legal authority. Given the seriousness of the threat posed by ocean acidification and its interaction with other water quality problems, the state should consider the utility of these other methods for reducing pressure on the aquatic environment.

6.) Increase Public and Policymaker Awareness

There can be no successful program to reduce the ocean acidification impact on Delaware's resources without the support and guidance of the public and informed representatives and officials. The working group's efforts will be well-served by investing time early on in briefing executive officials, state legislators, and local government officials and considering their needs and concerns. The committee should post information about its work on a public website and share information about progress with public information officials. Funded researchers should be required to share data and should be included in briefings with policymakers and the public. When DNREC is sharing information about climate change with the public, ocean acidification should be one of the topics discussed.

Some work has been done at the national level at aquaria and zoos to test how informed the public is about ocean acidification. In the state, DNREC and Delaware Sea Grant regularly survey the public about environmental topics. Ocean Acidification should be on the list of questions. It might also be useful to conduct a survey of resource managers, local officials, affected industries and interested groups (environmental groups, recreational fishing clubs) to determine their level of knowledge on the topic and their priorities and concerns. The survey would provide important feedback for the working group's priority setting and help determine what types of public and policymaker education efforts could be useful.

CONCLUSION

The State of Delaware has a wealth of aquatic resources and a proud history of protecting them. Ocean acidification is a threat to our estuary and coast and it is already underway. But, Delawareans believe that they can have an impact on our environment, even in the face of climate change, and the science supports their optimism. The state has the opportunity to act now to minimize damage and prepare for change. A partnership of state agencies, businesses, citizens, scientists and policymakers working together to define our existing assets, our unanswered questions and needs, and our priorities for ocean acidification-related investment could give us the best chance to protect communities and wildlife, both in Delaware and in the Mid-Atlantic region. Ocean acidification does uniquely challenge those of us living near the Rubik's cube of estuarine and coastal chemistry, but this report offers us a path forward to a healthier ocean.

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