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HEARING ON:
ATMOSPHERIC SCIENCE RESEARCH AND FORECASTING INNOVATION

SENATE COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION
SUBCOMITTEE ON SCIENCE, OCEANS, FISHERIES AND WEATHER

MAY 16, 2019

My background

For the last thirty years I have devoted my life to the study of the oceans. For twenty-six of those years I was a college professor who ran my own laboratory focused on the study of nutrients and how they control the growth of phytoplankton and bacteria at the base of the ocean food web. I have participated in over 50 research expeditions from the Arctic to the Antarctic. Over the last decade, I have also taken what I learned in the ocean, and applied it to help water reclamation facilities.

Throughout my career I have been committed to service – to science and this country. I was a member of the Ocean Carbon and Biogeochemistry Scientific Steering Committee and the U.S. Carbon Cycle Science Plan Working Group, and have served on numerous review committees for tenure and promotion, research funding, and programs, including as chair of the institutional review of the Woods Hole Oceanographic Institution.

I was elected member-at-large and then president of the Association for the Sciences of Limnology and Oceanography, the largest international scientific society dedicated to the aquatic sciences. I have also served as member-at-large, treasurer and chair of the Council of Scientific Society Presidents, an organization that represents over a million scientists in the U.S. across all scientific disciplines.

From 2012 to 2015, I served at the National Science Foundation as section head and then director of the Division of Ocean Sciences where I was responsible for programs across all ocean disciplines as well as major oceanographic facilities including NSF use of the U.S. research fleet, ocean observing, and the ocean drilling program. It is an honor to continue that service by providing testimony to this committee. I offer these thoughts as a citizen based on my experience as a scientist, an educator, and a mother.

I also note that I am a middle child; we tend to be the peacekeepers. I was raised by very conservative parents that I respected and adored and I have spent my life working with many very liberal individuals who are like a second family. This means I have spent my entire life trying to look at both sides of what can be very contentious issues. When it comes to the ocean there are many.

Introduction

In my comments, I will focus on climate, which is the average weather conditions on the planet over decades. This is in contrast to weather, which is the day to day state of the atmosphere and how it changes over days to weeks. One way to think about this is that climate is what you expect, but weather is what you get on any given day.

My take home message is that the United States should commit to a sustained investment in four things – climate modeling, collecting the global ocean observations of key physical variables, developing the tools needed to generate global observations of key chemical and biological parameters, and training the workforce needed to do all three successfully.

There is an abundance of scientific literature on the ocean's impact on climate and I will not do it justice here. In the time and space allowed I have tried to provide a brief tutorial of the basics that I would want all of our elected officials to know. I direct interested readers to a number of summary reports including Sustaining Ocean Observations to Understand Future Changes in Earth's Climate (National Academies 2017), the National Climate Assessments (Jewett and Ramanou 2017; Taylor et al. 2017; Hayhoe et al. 2018; Pershing et al. 2018), the State of the Carbon Cycle Reports (USGCRP 2018), and the many products developed through the Intergovernmental Panel on Climate Change (IPCC).

A. Why the climate is changing

Life exists on Earth because the planet has a blanket of atmospheric gases, including water vapor, carbon dioxide, and methane, that acts like the glass of a greenhouse and retains some of the energy from incoming solar radiation. Over the past 100 years, mankind has taken carbon buried deep within the ground as fossil fuels, and burned it to power the incredible technological advances started during the Industrial Revolution. The result raised the standard of living for billions of people around the globe. It also increased the concentration of these greenhouse gases in our atmosphere resulting in an average increase in global temperature from 1901 to 2016 of ~1.0°C (1.8°F; Hayhoe et al. 2018).

This massive alteration of Earth's atmosphere has had a profound impact on our oceans, which have absorbed more than a quarter of the carbon dioxide released. Here I highlight two direct effects this increase in greenhouse gas concentrations have had on our oceans – they are now warmer and the pH of the water has declined, making the ocean more acidic. Both of these changes have had an effect on the ocean's role in climate.

B. Ocean warming

Every year, humans release about 10 gigatons (36 billion tons) of carbon into the atmosphere from burning fossil fuels and other activities (Le Quéré et al. 2018). In 2016, atmospheric levels of carbon dioxide passed 400 ppm, a striking milestone and a dramatic increase from pre-Industrial levels of 280 ppm. This huge surge in the levels of carbon and other greenhouse gases blanketing the atmosphere traps excess heat in the Earth's climate system.

The oceans have absorbed 93 percent of this excess heat and store it for two main reasons. First, water has the highest specific heat capacity of any common material, meaning that it can absorb a great deal of heat before its temperature actually increases. Second, the global ocean is vast, covering 71 percent of the Earth's surface with an average depth of 4 kilometers (12,123 feet). This incredible volume makes it a huge reservoir for heat that is continuously distributed by currents and other circulation processes.

The highest degree of warming has taken place in the upper 75 meters (246 feet), as this upper layer lies closest to the warming atmosphere. Average global temperatures in the surface ocean have increased by 0.7 ± 0.08 °C (1.3° ± 0.1°F) per century between 1900 and 2016 (Jewett and Romanou 2017). The upper ocean also mixes vigorously, distributing the heat it absorbs. As more energy enters Earth's climate system, heat penetrates deeper into the ocean. Warming at the poles is especially impactful because these are the sites of deep ocean water formation. The combination of ice formation and extreme cold makes the waters in the North Atlantic dense relative to surrounding waters. These dense waters sink carrying heat to the ocean's interior.

Most of the remaining 7 percent of this heat goes into melting sea ice, glaciers, ice caps, and warming the continent's land mass. Only a tiny fraction goes into warming the atmosphere, but even that is felt in rising global temperatures. The six warmest years on record have all occurred since 2010 (NOAA State of the Climate Report 2019). While there is much debate over the record of increasing air temperatures, the ocean does not have parking lots or heat island effects and yet still we see significant increases in temperature.

The complex interactions between continued greenhouse gas emissions, the resulting energy imbalance, and changes in ocean heat storage and transport will largely control the impacts of anthropogenic climate change. I focus on five critical impacts here – melting of sea ice, sea level rise and coastal flooding, changes in the distribution and migration of marine organisms, the decline of coral reefs and deoxygenation of the ocean.

1. Melting of sea ice

The Arctic Ocean is important to the world's ecology, climate, and economy. Due to the shape of the planet, more incoming solar radiation concentrates at the equator than at the poles. The atmosphere and ocean currents address this energy imbalance by transporting heat away from the equator. This process has driven annual average temperatures in the Arctic to increase more than twice as fast as the global average, resulting in substantial loss of sea ice and glacial mass. Climate models using the IPCC "business as usual" scenario predict average Arctic temperatures will increase 7°C (45°F) by the year 2100.

Since 1979, the annual average extent of Arctic sea ice has decreased 3.5 to 4.1 percent per decade, including an 80 percent loss in summer sea ice volume (Comiso and Hall 2014; Vaughan et al. 2013). The melting of sea ice now starts 15 days earlier than it did in the past, and it is predicted that the Arctic will be nearly free of late-summer sea ice by the middle of this century (Taylor et al. 2017).

The lack of summer Arctic sea ice is increasing seaside erosion, undercutting villages, and washing away infrastructure. Alaskans are being forced to change their hunting strategies and even the locations of whole communities. From 2010 to 2017, I made seven trips to Barrow, Alaska, the northern most village in the U.S. In that short time, the changes to the region and community have been profound including the impending destruction of the main road from Barrow to Point Barrow due to erosion from the sea.

The effect of sea ice loss is profound because it is a key part of polar ecosystems. Large blooms of algae occur at the ice edge and form the base of the Arctic Ocean food web (Arrigo 2014). As ice coverage declines, the timing and location of the ice edge blooms change, as does critical habitat for more than a thousand species, including polar bears, seabirds, and seals. Many organisms hunt, give birth, migrate and shelter on ice, and the loss of ice is causing declines in a number of species (Laidre et al. 2015). As one example, walruses are moving farther from shore as the sea ice extent shrinks, and hunters from native Arctic communities that rely on them must now travel further across open water, threatening both people's safety and traditional ways of life.

Shrinking ice cover is also making the Arctic more accessible to shipping, with access by various countries and commercial entities. This brings both new opportunities and risks. The challenges that accompany greater access include protecting the border from new threats to national security, a heightened threat of oil spills and illegal fishing, and the need to update severely outdated nautical charts and put search and rescue plans in place.

2. Sea level rise and coastal flooding

Sea level is rising as a result of warming ocean temperatures and the melting of ice on land, such as glaciers and ice sheets. Warming water temperatures contribute to sea level rise because of thermal expansion – warm water takes up more volume than cooler water. Since 1900, average sea level has risen by about 16 to 21 cm (7 to 8 inches) globally with about a third of the increase due to thermal expansion. Even more alarming than the amount is that nearly half of this increase has occurred since 1993. Sea level continues to rise at a rate of about one-eighth of an inch per year (Hayhoe et al. 2018).

The ultimate magnitude of sea level rise will vary based on how land ice responds to continued warming. Predictions for the century between 2000 and 2100 vary from one to four feet of sea level increase, with extreme increases of over eight feet if the Antarctic ice sheets collapse. If the ice sheet on Greenland were to melt, sea level could increase by an incredible 21 feet. These scenarios are unlikely, but I note that past increases have been larger and occurred more rapidly than expected. As a nation, we need to prepare for the worst.

There will be many consequences of higher sea levels. Destructive and deadly storm surges will reach farther inland, bringing more frequent flooding with high tides. These floods are disruptive and expensive. Today, nuisance flooding is estimated to be from 300 percent to 900 percent more frequent within U.S. coastal communities than 50 years ago (Sweet et al. 2014).

As ocean and atmospheric warming trends persist, sea level rise over the next centuries will ramp up to rates significantly higher than what we see today. Nearly 40 percent of people in the United States live in high-population-density coastal areas, where they will be subject to the flooding, shoreline erosion, and hazardous storms that come with rising sea levels. These impacts will also be felt globally – eight of the 10 largest cities in the world are near a coast as are four of the 10 largest cities in the U.S.

Specific locations will experience sea level rise differently based on local factors, such as subsidence and rebounding from natural geological processes, changes in regional ocean currents, and withdrawal of groundwater and fossil fuels. Sea level rise has already increased the frequency of flooding at high tide by a factor of 5 to 10 since the 1960s for several U.S. coastal communities. The frequency and extent of tidal flooding are expected to continue to increase in the future and its anticipated that there will be more severe flooding associated with coastal storms, hurricanes and nor'easters (Sweet et al. 2014). The infrastructure essential for local and regional industries in urban environments will be threatened, including roads, bridges, oil and gas wells, and power plants.

3. Changes in the migration and distribution of marine organisms

Increases in water temperatures and its associated effects have caused alterations to global patterns of ocean and atmospheric circulation, precipitation, and nutrients. Collectively, these effects are having a drastic impact on the abundance, diversity, and distribution of marine organisms – from the smallest bacteria to the largest fish.

Most of the life in the ocean is microscopic. While we cannot see these microorganisms without a microscopic, they produce half of the oxygen we breathe and form the base of ocean food webs. As most are single-celled organisms that can only drift in the water column, these vital plankton are highly vulnerable to ocean changes.

Broadly speaking, the ocean has two parts – a warmer, less dense layer at the surface that receives sunlight but has low nutrients (because the microorganisms have taken them all up) and a deep layer that is denser and colder, with no light but lots of nutrients (because decomposing organisms sink and release nutrients as they decompose). Rapid warming of surface water is increasing the temperature difference between these layers, increasing the stratification of the ocean and preventing the surface and deep water from mixing efficiently. As a result, most phytoplankton have a harder time staying near the sunlight that they need to grow, and the greater stratification restricts the delivery of nutrients phytoplankton need from the deep ocean.

These changes to the base of the ocean food web reverberate through other marine species including the fishing sector, which contributes over $200 billion in economic activity each year and supports 1.6 million jobs (NOAA Fisheries 2017). The species this industry relies upon are changing as a result of warming waters. These shifts in species distributions are complicating fishery management by changing the nature of traditional fisheries and efforts to protect endangered species.

These shifts are especially prominent off the U.S. east coast. For example, surveys conducted by state and federal agencies documented a number of shifts in distribution in fish, shellfish and other species along the mid-Atlantic with a trend toward poleward movement and/or movement to deeper cooler water (Lucey and Nye 2010). Recent research at Bigelow Laboratory shows that copepods (tiny crustacean that eat phytoplankton and are then eaten by higher organisms) are less viable if grown in warmer waters. Shrinking copepod populations will threaten numerous marine species that rely on them for nutrition, including the endangered North Atlantic right whale (Record et al. 2019).

I have provided a few examples of shifts in the distribution of organisms but I note that detecting and quantifying these changes are a challenge because each species within a community may response differently due to differences in their life history, where they live, and what they eat. Organisms also vary with respect to the outside forces that affect them such as fishing, destruction of their habitat or pollution. Due to this complexity, detecting and understanding shifts in species and populations requires a commitment to long-term monitoring programs, which have historically been very difficult to maintain.

4. Coral reef decline

Coral reefs are the foundations of many tropical ecosystems. Temperature is a powerful controlling variable for the health and location of coral reefs, and many exist at or near their upper temperature limit (Schoepf et al. 2015). As a result, ocean warming has had a devastating effect on coral reefs around the world. When corals are exposed to waters even slightly above their temperature maximum, they can release the symbiotic algae, called zooxanthellae, that live within their tissues. This process is known as bleaching because of the stark white color it turns corals. The symbiotic algae provide vital nutrients to the coral, and so bleaching often kills them.

During the last 30 years, there have been several global-scale coral bleaching events (in 1987, 1998, 2005, and 2015–2016) that have resulted in a dramatic reduction of live coral. This puts the entire community of plants and animals that rely on the reefs in jeopardy. In the United States, mass bleaching events and outbreaks of coral diseases have occurred in the waters off Florida, Hawaii, Puerto Rico, the U.S. Virgin Islands, and the U.S.-Affiliated Pacific Islands (Miller et al. 2009; Rogers and Muller 2012).

In addition to the direct physiological stress of elevated temperatures, ocean warming also increases the incidence of coral disease, and ocean acidification affects the ability of corals to produce their calcium carbonate structures (discussed further in section B below). When these effects compromise reef-building corals, the entire reef ecosystem becomes threatened (Jones et al. 2004). This includes a vast number of invertebrates and fish, organisms that many coastal communities depend on for subsistence. Corals also provide storm protection to coastal ecosystems and can form the basis of local or regional tourism economies (Prachett et al. 2008).

5. Low oxygen

Oxygen makes up 21 percent of the air we breathe and supports life on Earth, and half of this oxygen was produced by phytoplankton in the ocean. In water, oxygen exists in a dissolved form and acts as a limiting resource that controls the growth of many marine species. One consequence of climate change is the loss of oxygen from the oceans, known as ocean deoxygenation (Deutsch et al 2011).

Levels of oxygen in the ocean depend on a balance between oxygen production through phytoplankton photosynthesis, depletion through respiration by animals, and physical mixing processes. Climate change is shifting this balance in several ways. At the most fundamental level, warmer water holds less oxygen than cold. As the oceans warm, they lose their ability to physically hold oxygen. The same holds true for greenhouse gases like carbon dioxide and methane.

In addition, the surface ocean is warming fastest due to its proximity to the atmosphere. This makes the surface water less dense and less able to mix with the colder, denser water below, limiting the distribution of oxygen. At the same time, global ocean circulation patterns are shifting with climate change. Slower circulation and more upwelling of oxygen-poor deep water are further decreasing oxygen levels in the ocean.

Long-term monitoring efforts reveal that oxygen concentrations have declined during the 20th century, and the IPCC 5th Assessment Report predicts that they will decrease 3-6 percent during the 21st century due to ocean surface warming. In coastal regions, low oxygen is a particularly devastating problem and dead zones where most organisms cannot live because of insufficient oxygen have been reported for more than 479 systems and their numbers have doubled every decade since the 1960s (Diaz and Rosenberg 2008).

Changes to biological processes are also contributing to this issue. Warmer water temperatures increase oxygen demand from organisms, leading to the faster depletion of available oxygen and threats to a vast range of species, including those that comprise valuable fisheries. For example, off the coast of California, waters between 200 and 300 meters have lost 20-30 percent of their oxygen in the last 25 years (Bograd et al. 2008), threatening important fisheries. In the tropical Atlantic Ocean, the vertical habitat of tuna and blue marlin reduced by 15 percent between 1960 and 2010 due to expanding oxygen minimum zones (Stramma et al. 2012; Schmitko et al. 2017).

C. Ocean acidification

In addition to warming, excess carbon dioxide in the atmosphere has a direct and independent effect on the chemistry of the ocean, which can also impact future climate. Ocean acidification is the process of carbon dioxide being absorbed by the oceans and causing significant changes to seawater chemistry. Global chemical processes keep gasses in the ocean and the atmosphere in equilibrium. While humans have drastically increased the amount of carbon dioxide in the atmosphere, the ocean has been working to keep up. About a quarter of the carbon dioxide we generate through industrial activity ends up in the ocean, and the resulting change in chemistry has caused the surface ocean to become 30 percent more acidic. This has occurred at a rate at least 10 times faster than any natural acidification event in the past, and affects everything from chemical processes to sea life.

When carbon dioxide in the atmosphere dissolves in seawater, it changes three aspects of ocean chemistry. First, it increases levels of dissolved carbon dioxide and bicarbonate ions, which are the fuel for photosynthesis in phytoplankton and plants. Second, it increases the concentration of free hydrogen ions, which makes the water more acidic. Third, it reduces the concentration of carbonate ions. Carbonate is critical to many marine organisms, which use the mineral calcium carbonate to form their shells or skeletons. For some species, rising temperatures and decreasing oxygen levels in the ocean may exacerbate the effects of ocean acidification.

The cold temperature of high latitude ecosystems results in greater carbon dioxide solubility making polar regions highly vulnerable to ocean acidification. Sea ice loss is also causing Arctic waters to acidify faster than expected. Further, acidification along the United States coast is greater than the global average for a number of reasons, including the natural upwelling of acidic waters off the Pacific Northwest and California coasts, changes to freshwater inputs in the Gulf of Maine, and anthropogenic nutrient input into urban estuaries. Here I will focus on two major consequences of ocean acidification – changes to the ocean carbon cycle and the impact on organisms and the industries built around them including fisheries and aquaculture

1. Changes to the ocean carbon cycle

Carbon is recycled and reused through biological and physical ocean processes including photosynthesis, respiration by animals, and mixing within the ocean. The carbon cycle drives important biogeochemical processes that shape the character of the global ocean and planet as a whole. When organisms die, they sink, bringing the carbon that composes their bodies into the deep ocean. This is referred to as the biological pump because it pumps carbon from the surface to the deep ocean and can sequester carbon away for hundreds of years. The oceans are by far the largest carbon sink, or storage reservoir, on Earth.

The combined effect of ocean warming and acidification lowers the ability of the ocean to take up additional carbon dioxide in three general ways. First, as noted above, warmer water can simply hold less gas than colder water. Second, the warmer water in the surface ocean becomes, the more stratified the water column will be. Greater stratification reduces mixing and so reduces the ability for carbon dioxide dissolved in surface water to be mixed into deeper waters. Third, it is generally harder for organisms to build shells out of calcium carbonate in more acidic waters. This means that phytoplankton that build shells (such as coccolithophores), and are therefore heavier and so sink faster, are at a disadvantage. As the ocean continues to acidify, any selection away from organisms that build shells and towards organisms that do not, will likely weaken the biological pump and decrease the transport of carbon into the deep ocean as phytoplankton die. These effects are already being seen and the oceans are becoming less able to absorb carbon dioxide (e.g. Khatiwala et al. 2016).

2. Threats to organisms, including fisheries and aquaculture

The impacts of ocean acidification are diverse. Although certain species are favored by more acidic waters, ocean acidification appears to negatively impact more marine species than it helps. Organisms that use carbonate minerals to build skeletons or shells struggle with this basic function in more acidic waters. Organisms like clams, mussels, and phytoplankton that use calcium carbonate to build shells and other structures are important in environments and economies around the globe. Under the IPCC low emissions scenario, seven to 12 percent of calcifying species would be significantly affected by lowering pH, and 21 to 32 percent of calcifying species would be impacted under the high emissions scenario (Azevedo et al. 2015).

Ocean acidification also appears to favor some toxic phytoplankton species that form harmful algal blooms, allowing them to become more abundant in changing ecosystems (Riebesell et al. 2018). Including freshwater and marine ecosystems, harmful algal blooms are a significant environmental problem in all 50 states (EPA 2013).

Entire coral reef ecosystems are also severely threatened by ocean acidification. Corals depend on calcium carbonate to build their exoskeletons, and acidification impedes this process. The acidic water also literally dissolves coral structures, and the bulk of a coral reef itself. Many reefs around the world are dissolving faster than they can build themselves back up. In addition to forming the foundations of ecosystems, corals also provide storm protection to coastal ecosystems and can form the basis of local or regional tourism economies. By the end of this century, the loss in recreation from coral reefs in U.S. is expected to reach $140 billion (Pershing et al. 2018).

Some of the animals at risk from acidification also comprise lucrative fisheries in the U.S., like lobsters in the Northeast and squid in California. These animals are physically compromised by acidification, and they may find it harder to get the food they need in acidifying oceans. Acidification impairs the senses of some fish and invertebrates, causing them to misinterpret cues from predators and engage in risky behaviors, like swimming far from home. Damage to key phytoplankton and zooplankton species can reverberate through entire food webs, affecting the fisheries that they support.

The U.S. aquaculture industry is already shifting in response to ocean acidification. Larval shellfish cannot build shells under high acidity, and high mortality rates have afflicted the Pacific Northwest’s $270 million shellfish industry since 2005. The poor conditions have prompted some shellfish aquaculture facilities to relocate. In Maine, some shellfish farmers are growing kelp in an effort to improve local water quality and the health of their stocks.

D. Feedback loops between the ocean and climate

Natural systems have feedback loops that allow them to adjust to changes in the environment. In Earth's warming climate system, a positive feedback loop would increase the warming, while a negative feedback loop would reduce it. The changes in the ocean described above will affect climate in a number of different ways. Unfortunately, the feedbacks are largely positive and work to exacerbate warming.

For example, the decline in sea ice has a direct positive feedback on warming. Light colored surfaces reflect more incoming solar radiation back into space than darker surfaces. When light colored ice melts, it exposes blue ocean water. This blue ocean water absorbs more energy, thus creating a positive feedback loop. The warmer it gets, the more blue water exposed, the more solar radiation absorbed to further increase the temperature.

Ocean acidification contributes to another positive feedback loop with a warming climate. As the ocean acidifies, phytoplankton that produce calcium carbonate shells will be selected against and phytoplankton that do not build shells will have a competitive advantage. The fewer phytoplankton that build calcium carbonate that sink into the deep ocean, the less carbon dioxide the ocean will be able to adsorb, and the higher the concentration of carbon dioxide in the atmosphere available to continue to warm the planet.

E. Taking action – The need for sustained ocean observations

Earth's climate is now changing more rapidly than at any time in human history. The accumulation of greenhouse gases in the atmosphere will continue and the impacts describe above will worsen. As a result, this country will be increasingly called on to make complex decisions about how to manage and mitigate the impacts of climate change. We will be better able to make these decisions if we have the tools in hand to model and predict changes in the climate system. This will require a national commitment to increase investment to advance the field of climate modeling, continued support for sustained, high quality, ocean observations to power the models, and targeted experimental and field work to address outstanding questions raised by model uncertainty surrounding the biological and chemical processes that are key drivers of the ocean carbon cycle.

1. Modeling

To study how the atmosphere and the different layers of the ocean interact to predict changes in climate, scientists build computer models. At a basic level, within the model the surface of the Earth is divided into squares and each square includes a series of mathematical equations that represent the processes being modeled. These equations are based on physical and chemical laws. The more refined the model, the smaller squares and the more information they contain.

Modelers have a saying – “garbage in, garbage out.” For a model to accurately represent that is happening in the real world, it must have data and lots of it. To predict changes in climate, models need data on the temperature, salinity, and carbon concentrations in the surface and deep ocean, global sea ice distribution, surface stress and surface and deep ocean currents, and heat flux. They also need data on the movement of freshwater from the land via rivers, glaciers, and ice sheets. These data need to be collected over decadal time scales and be global in scope. To predict climate, we also need to understand ocean biology because biology controls carbon uptake and regeneration at the base of the ocean food web.

2. Types of observations needed – heat, freshwater, and carbon

A common tool used by scientists is the construction of budgets for important variables in the model. As an oceanographer who studies nitrogen, I would construct nitrogen budgets to show where nitrogen was coming from, such as a river or a waste water treatment plant, and where it was going, such as into phytoplankton or bacteria. A recent National Academies (2017) report identified three global budgets that were needed to understand climate – heat, freshwater, and carbon. They were selected because they each are necessary to understand the climate system and to predict how it will change in the future. To truly quantify these three budgets requires a global ocean observing system where continuous, calibrated measurements are made over decades.

Heat – A heat budget is the balance between the heat absorbed by Earth from incoming solar radiation and outgoing heat escaping from Earth in the form of radiation. Slight changes in the balance would lead to Earth getting progressively warmer or cooler with each passing year.

Over the past 100 years, there has been a net gain in heat on Earth’s surface. Ninety percent of this gain has been through ocean warming. The adsorption of heat by the ocean is one the reason why atmospheric temperatures at the Earth’s surface have not increased more (Fyfe et al. 2016). This heat is transported throughout the surface and deep ocean currents. Currents in the deep ocean are controlled by small variations in temperature and salinity and are known as thermohaline currents. The greatest challenge for measuring global ocean heat content has been to sample a large enough number of sites around the globe and at enough depths throughout the ocean.

Freshwater – Less than 4 percent of the water on Earth is freshwater. Sixty-eight percent of this freshwater is locked up in ice and glaciers and another 30 percent is groundwater. Understanding the freshwater budget is important to understanding the salinity of the ocean. Salinity and temperature determine the density of water and so is an important control on ocean stratification and ocean circulation. Generally, temperature is more important and the basic structure of the ocean water column as warm water at the surface and progressively colder water as one moves deeper. Freshwater, and its effect on salinity, however, can change this relationship drastically. Areas where there is a lot of freshwater input, such as at a river outflow, regions with high rates of precipitation, or where sea ice is melting are areas where salinity is reduced making the water less dense. This less dense water remains at the surface, creating a barrier to mixing with the water below. This stratification reduces mixing of heat and gases between the surface and deep ocean thus impacting the heat balance in the region.

Carbon – The global carbon cycle is made up of pools of carbon and the processes that move this carbon from the atmosphere, surface and deep ocean and the sediment below. The cycle includes inorganic carbon, which is non-living carbon such as carbon dioxide and organic carbon, which is carbon that have been incorporated into organisms or the dissolved organic carbon they produce. This cycle is important to climate for a number of reasons, but primarily because of its control on concentrations of the greenhouse gas, carbon dioxide, and the huge effect carbon dioxide has on the heat balance of the planet.

An understanding of the carbon budget is essential to predicting future atmospheric carbon dioxide concentrations under different scenarios. Closing the carbon budget will require sustained observations of how much carbon dioxide the ocean absorbs and what happens to that carbon once it enters the ocean. This information is needed to predict how much carbon dioxide will be absorbed by the ocean in the future and the impact it will have on ocean acidification.

3. How do we collect the data we need?

We are not currently able to close the budgets described above, meaning that there are unaccounted for sources or sinks of heat, freshwater, and carbon in the ocean. To address this deficit, we need to develop methods or improve existing methods for some parameters and expand observations into areas of the ocean that are poorly sampled.

A successful global ocean observing system will use a suite of measurement and instrument approaches to provide complete coverage at the time scale of relevance to the measurement being taken. There are a number of ways to collect ocean data including the use of unmanned autonomous platforms such as satellites, buoys, floats, gliders and moorings. All of these approaches require that methods and instrumentation are available and able to withstand the incredibly harsh, corrosive ocean environment.

Suitable approaches exist for many physical and a few chemical variables such as temperature, salinity, the strength and direction of currents, carbon dioxide concentrations and pH. In the case of most chemical and biological measurements (such as trace metals, bacterial abundance, phytoplankton pigments, grazing rates to name just a few) autonomous methods and instrumentation do not exist or are cost prohibitive. These data can only be collected by scientists on board ships and so will remain severely limited in number and geographic scope. This lack of data is a strong impediment to understanding Earth's climate system.

4. International cooperation

The United States has been a leader in the development and deployment of ocean observing systems. We cannot do it alone, however, nor should we want to. Support for

United States scientists to participate and lead international programs in climate modeling and ocean observations should be a priority. Coordinated international programs provide the opportunities to share the financial cost of long-term observing systems, improve the quality of the measurements taken through a robust program of intercalibration, and serve as an important route for science diplomacy. When nations collaborate to address common problems, partnerships are forged that can extend well beyond the original issue that brought the nations together.

An excellent example is the ARGO float program, which collects high quality profiles of temperature and salinity in the upper 2000 m of the ocean. There are currently 3875 ARGO floats in the ocean, purchased and deployed by 34 countries with nearly another 20 countries contributing to the program through field assistance or data analysis. The floats move passively with the current, slowly moving up and down the water column. When they reach the surface, they transmit their position and the data they collected to a data repository. ARGO has transformed our understanding of ocean currents. Additional sensors for oxygen and nitrogen (nitrate) have been developed and deployed on a small subset of the floats. Investment to increase the number of chemical and biological parameters that can be measured with the floats would be money well spent.

5. Workforce development

To address the issues outlined above, the United States will also require a highly skilled workforce. Increasing investment now into STEM education across the United States is necessary to support a sustained system of climate observations into the future. We also do not need to go it alone. For decades, the best and the brightest around the world wanted to come and be trained at institutes of higher learning in the United States and we welcomed them. We are fortunate that many of them chose to stay, and our nation benefitted immensely from the skill, passion and innovation they brought. Those that chose to return home or go elsewhere, took with them a better understanding of our republic and lasting relationships with our citizens.

We now live in an era marred by terrorism and in our fear, we are making it increasingly more difficult for students to come to the United States and then to stay once they are trained. If I had to name one thing that most frightens me about the future of this country – this is it. The technological challenges in the future will be immense and we will only solve them by bringing together a wide array of viewpoints, perspectives, and experiences from across this great nation and around the world. I want the best and the brightest to be on our team. We should welcome them, train then well, and then staple a green card to every PhD diploma to encourage them to stay.

F. Conclusion

With the large increase in greenhouse gases that mankind has released into the atmosphere, we are conducting a massive experiment on the only planet we have. To know how best to protect ourselves from and respond to the changes in our climate, the United States should commit to sustained investment in four things – climate modeling, collecting the global ocean observations of key physical variables, developing the tools needed to generate global observations of key chemical and biological parameters, and training the workforce needed to do all three successfully. I emphasize the word sustained, because programs that can lay out workplans over the course of a decade or more will be more productive and better able to leverage resources than shorter term initiatives. Finally, the priorities for initiatives in modeling and data collection should be generated by leaders in the respective scientific disciplines and be done in the context of international collaborations.

G. Citations

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