

**Prepared Statement of
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**Before the House Science, Space, and Technology Committee
United States House of Representatives**

An Update on the Climate Crisis: From Science to Solutions

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Introduction

I am providing this testimony in my capacity as Deputy Director and Vice President for Research at Woods Hole Oceanographic Institution (WHOI). Woods Hole Oceanographic, with six research departments, more than 40 centers and labs, and nearly 1,000 scientists, engineers, technicians, and staff, is the world's leading, independent non-profit organization dedicated to ocean research, exploration, and education. Prior to my position at WHOI, I was a professor at Boston University for 27 years and, from 2015-2018, I had the privilege to serve the National Science Foundation as the Director of the Division of Ocean Sciences. While at the NSF, my team and I oversaw an annual budget of about \$370 million devoted to the research, education, and technology grant programs, as well as critical infrastructure, such as the Academic Research Fleet, Ocean Observatories Initiative, and Scientific Ocean Drilling. I was also involved with many other activities in marine policy with the Office of Science and Technology Policy that facilitated collaborations with NOAA, Office of Naval Research, NASA, BOEM, and other agencies. As such, the testimony I present here is based on my research and teaching experiences, my work with the federal government, and engagement with the ocean research and technology community writ large.

In my testimony, I hope to achieve the following:

1. Provide a summary of the key findings from the IPCC's Special Report on Ocean and Cryosphere in a Changing Climate (SROCC).
2. Describe some of the impacts of the environmental changes discussed in SROCC have for the security of U.S. economy and workforce, the quality of life for our citizens,

and national security, including with the renewed Great Powers Competition with China and Russia.

3. Make some specific recommendations for you to consider as you make decisions regarding investments in the scientific enterprise overall, and with regard to climate specifically.

4. Reinforce the following “take home messages”:

- The ocean must be included in any comprehensive discussion of climate legislation and policy, as well as of economic and national security. It is the key driver of much of what we land-bound humans experience in our weather patterns; the relationships between food, water, and energy; and our economic and national defense.
- Building on previous accomplishments by you and your predecessors, we as a nation must make bold and innovative investments in the ocean observation enterprise so that we may increase quantification of key climate processes—heat, carbon, and freshwater budgets—and refine models and predictions to the degree required for our economic and social well-being. It will only be with significant advancements in data coverage and quality that we will truly be able to take advantage of the scientific and engineering capabilities of our nation to further our economic and social well-being.
- The societal value of ocean observations is directly tied to its relevance to policy-makers in formats that clearly indicate the level of scientific confidence in its credibility and the clarity of any subsequent analysis.
- The integration of climate and weather modeling with risk assessment and risk management models will help align climate policies with economic incentives and disincentives. These climate policies that you are considering have the potential for dramatic and positive effects on the U.S. for generations to come, and in order to get it right you will need the very best understanding of risk and uncertainty scientists can provide. To reduce those risks and uncertainties requires vastly strengthened ocean observations.

My focus here is on the oceans. While there are many areas in need of policy and fiscal attention to help address the challenges accompanying climate change, throughout my testimony I will focus on the need for a significantly enhanced ocean observation

enterprise across scientific disciplines, geographic regions, and temporal and spatial scales in the ocean.

I want to be clear that the scientific ocean observation enterprise includes not only the infrastructure and technology necessary for the actual capture of data, but the synthesis and processing of data and its integration into climate, weather, and ocean models to advance our prediction and forecasting capabilities. It is ships, buoys, and satellites, and the shore-based infrastructure to support them. It includes high performance computers and people. It includes novel and innovative technological developments, including battery development and miniaturization. It includes artificial intelligence and machine learning. In essence, it includes everything that other scientific and technological sectors are wrestling with, yet done in the harsh and corrosive world of the ocean. The difficulties of the ocean environment in which we work are rivaled only by those of outer space.

For oceans and climate, there are numerous needs given the diversity of challenges and scientific disciplines, which spread across the physical, biological, chemical, and geologic sciences. At the highest level, many of these needs can be captured under the need to better understand the heat, carbon, and freshwater “budgets,” where budget is a scientific term focused on the underlying processes driving these cycles. There are many individual scientific focus areas within each of these processes or budgets, and—similar to how Congress must deal with financial budgets—these scientific processes are interconnected.

For example, the future rate of sea level rise can only be understood if we understand the melting of icecaps and glaciers, how much the surface and depth of the ocean is warming since water expands as it warms, and how ocean circulation patterns influence both polar ice sheet melting as well as regional sea level rise. Similarly, ocean health is closely tied to biogeochemical processes, so to understand the rate of increasing ocean acidification and its impact on marine ecosystems—including fisheries and corals—we need to better understand how carbon cycles through the ocean and how heat impacts this process. There are important other benefits to increasing our comprehending of these scientific functionings such as being better able to understand the transportation of pollutants such as microplastics throughout the global ocean. Additionally, a thorough understanding of the carbon budget and the ocean’s capacity to absorb carbon dioxide (and heat) is critical to improving our capacity to predict future atmospheric carbon dioxide concentrations under various greenhouse gas emission scenarios.

Summary of findings from the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate*

All people on Earth depend directly or indirectly on the ocean. It covers 71 percent of Earth's surface and contains 97 percent of the Earth's water. The ocean also supports unique habitats, many of them economically important, and hosts physical, chemical, biological, and geological processes that are integral components of the climate system through global exchange of water, energy, and many of the forms of carbon that exist in the Earth system.

The projected responses of the ocean to past and current human-induced greenhouse gas emissions and ongoing global warming include climate feedbacks, changes over decades to millennia that cannot be avoided, thresholds of abrupt change, and irreversibility. Human communities in close connection with coastal environments, small islands (including Small Island Developing States, SIDS), and polar areas are particularly exposed to ocean and cryosphere change, such as sea level rise and extreme events such as storm surge. The low-lying coastal zone is currently home to around 680 million people (nearly 10 percent of the 2010 global population) and is projected to reach more than one billion by 2050. SIDS alone are home to 65 million people around the globe. Other communities further from the coast are also exposed to changes in the ocean, such as through extreme weather events and shifting patterns of precipitation.

In addition to the role of the ocean and/or cryosphere within the climate system, such as the uptake and redistribution of natural and anthropogenic carbon dioxide (CO₂) and heat, the ocean provides to people worldwide food and water security, renewable energy, transportation, and benefits that support health and well-being, cultural identity, tourism, and trade.

Certainty and Uncertainty: "Calibrated Language"

The language in the report is very carefully chosen to depict the level of certainty of specific statements and I urge you to study this figure from the report itself before continuing with the rest of my testimony.

Step 1: Evaluate evidence and agreement

Observations Theory Statistics Models Experiments Process

✓ ✓ ✓ ✓ ✓ ✓

Sufficient evidence and agreement to evaluate confidence?

Step 2: Evaluate confidence

Agreement ↑

High agreement	High agreement	High agreement
Limited evidence (Emerging)	Medium evidence	Robust evidence (Robust)
Medium agreement	Medium agreement	Medium agreement
Limited evidence	Medium evidence	Robust evidence
Low agreement	Low agreement	Low agreement
Limited evidence (Limited)	Medium evidence	Robust evidence (Divergent)

Evidence (type, amount, quality, consistency) →

Confidence Language

- Very high
- High
- Medium
- Low
- Very low

Examples

- Glacier retreat and permafrost thaw have decreased the stability of mountain slopes and the integrity of infrastructure (**high confidence**) {2.3}
- There is currently **low confidence** in appraising past open ocean productivity trends, including those determined by satellites, due to newly identified region-specific drivers of microbial growth and the lack of corroborating in situ time series datasets. {5.2.2}

Sufficient confidence and quantitative/probabilistic evidence to evaluate likelihood?

Step 3: Evaluate statistical likelihood

Likelihood Language	Statistical Level (assessing change)	Statistical Range (assessing range)
Virtually certain	>99%	
Extremely likely	>95%	
Very likely	>90%	5–95% range
Likely	>66%	17–83% range
More likely than not	>50%	25–75% range
About as likely as not	33–66%	
Unlikely	<33%	<17% and >83% (both tails)
Very unlikely	<10%	<5% and >95% (both tails)
Extremely unlikely	<5%	
Exceptionally unlikely	<1%	

Example: statistical level

- Satellite observations reveal that marine heatwaves have **very likely** doubled in frequency between 1982 and 2016, and that they have also become longer-lasting, more intense and extensive. {6.4}

Examples: statistical range

- The AMOC will **very likely** weaken over the 21st century (**high confidence**), although a collapse is **very unlikely** (**medium confidence**). Nevertheless, a substantial weakening of the AMOC remains a physically plausible scenario. {6.7}
- Global mean sea level will rise between 0.43 m (0.29–0.59 m, **likely range**) (RCP2.6) and 0.84 m (0.61–1.10 m, **likely range**) (RCP8.5) by 2100 (**medium confidence**) relative to 1986–2005. {4.2.3}

Reference Change

Level of risk/impact

Deep uncertainty (Cross-Chapter Box 5 in Chapter 1)

- Evolution of the Antarctic Ice Sheet beyond the end of the 21st century is characterised by **deep uncertainty** as ice sheet models lack realistic representations of some of the underlying physical processes. {Cross-Chapter Box 8 in Chapter 3}

As described more fully in the Special Report itself, like other IPCC reports the statements regarding changes in the ocean and cryosphere are assigned a quantitative statement of confidence or likelihood (e.g., “virtually certain”, “exceptionally unlikely”, etc.). This schematic demonstrates the IPCC usage of this calibrated language, with examples of confidence and likelihood statements from the report. You will immediately note that the Report’s usage of phrases such as “very likely”, “likely”, or “high confidence” have far more meaning than when you or I use them when speaking casual English language to each other. This is a vitally important premise to consider when reading the report.

Findings

I would like to start this brief summary of the IPCC’s Special Report on Ocean and Cryosphere with the following statement taken directly from Section B2 of the *Summary for Policymakers, Projected Changes and Risks*:

“Over the 21st century, the ocean is projected to transition to unprecedented conditions with increased temperatures (virtually certain), greater upper ocean stratification (very likely), further acidification (virtually certain), oxygen decline (medium confidence), and altered net primary production (low confidence). Marine heatwaves (very high confidence) and extreme El Niño and La Niña events (medium confidence) are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken (very likely).”

This implications of this assessment and the relative confidence in the data supporting it is a sobering wake-up call about the important role the ocean plays in our planetary system. While it has been easier to ignore change in the ocean given that much of it occurs beyond our sight from land and also below the surface, mounting evidence of the impact the massive absorption of heat and carbon are having on physical, biological, chemical, and geological processes in the ocean indicates the ocean must be included in all considerations of weather and climate throughout the entire planet, including the deep interiors of continents very far from the oceans.

Perhaps the greatest benefit of this report is increasing recognition and public visibility of the ocean’s role both driving and being driven by Earth processes and the changing climate. It pulls together in one document the physical, chemical, biological, and geological processes occurring in the ocean and along our coast and considers them in the context of a changing climate. The ocean, with its capacity to absorb and distribute

vast amounts of heat and carbon on time scales that range from days to centuries to millennia, is at once the memory and the future of our climate.

Below are the key findings of the Special Report as they pertain to the ocean, which are compiled and summarized in the Summary for Policymakers. Rather than repeat their comments verbatim, I have encapsulated their main summary in straightforward points (albeit significantly shortened). The numbering system I use here (e.g., A1, A2, etc.) follows that of the Report, to assist further examination if you research beyond my abbreviated and heavily paraphrased presentation here. Further, it is important to explicitly point out that the High Level Findings summarized below are supported by multiple lines of evidence.

First, **What has been happening physically and chemically to the ocean?** As summarized in A1-A3 of the report, there have been significant decreases in the size and extent of ice sheets, glaciers, snow cover, and Arctic sea ice. Permafrost is thawing, as well. The ocean has warmed continually at least since 1970 and the rate of warming has doubled since 1993. Marine heatwaves are increasing in intensity and have very likely doubled in occurrence. Sea level is rising, and the rise is getting faster as more land-based ice melts and the oceans expand as they warm. Large storms are increasing in frequency and intensity, which further contributes to the impacts of sea level rise and increases in coastal and near-coastal hazards. Chemically, ocean acidification has increased and the upper ocean is losing oxygen.

Second, **What are the impacts on important ecosystems?** Focusing on the oceanic portion of this question (some impacts are more focused on the land and cryosphere, and thus I am not presenting here given the expertise of other witnesses), sections A5 and A6 document that since about 1950, many marine species across various groups have undergone shifts in geographical range and seasonal activities in response to changes in their habitats, including ocean warming, sea ice change and biogeochemical changes, such as oxygen loss. This has resulted in shifts in species composition, abundance and biomass production of ecosystems, and cascading impacts on ecosystem structure and functioning all the way from the equator to the poles. In some marine ecosystems species are affected by both fishing and climate change. Coastal ecosystems are affected by intensified marine heatwaves, acidification, loss of oxygen, salinity intrusion, and sea level rise in combination with adverse effects of human activities on ocean and land. Impacts are already observed on habitat quality and biodiversity, as well as ecosystem functioning and services.

How does this affect us? Again, focusing here on the oceanic portion of the report, sections A8 and A9 document that there have been both positive and negative impacts result for food security through fisheries, local cultures and livelihoods, governance, tourism, and recreation. The impacts on ecosystem services have negative consequences for health and well-being of all, including but not limited to Indigenous peoples and local communities dependent on fisheries. Coastal communities are exposed to multiple climate-related hazards, including tropical cyclones, extreme sea levels and flooding, marine heatwaves, sea ice loss, and permafrost thaw (high confidence).

What will the future look like? As presented in B1-B3, global-scale glacier mass loss, permafrost thaw, and decline in snow cover and Arctic sea ice extent are projected to continue in the near-term (2031–2050) due to surface air temperature increases, with unavoidable consequences for river runoff and local hazards. The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond. The rates and magnitudes of these cryospheric changes are projected to increase further in the second half of the 21st century if we live in a high greenhouse gas emissions scenario. However, if there are strong reductions in greenhouse gas emissions in the coming decades, further changes after 2050 may be reduced.

Over the 21st century, the ocean is projected to transition to unprecedented conditions with increased temperatures, greater upper ocean stratification, further acidification, decreasing oxygen, and perhaps altered net primary production. Marine heatwaves and extreme El Niño and La Niña events are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken. As with the cryospheric changes, the rates and magnitudes of these changes will be smaller under scenarios with lower greenhouse gas emissions.

Sea level continues to rise at an increasing rate. Extreme sea level events that are historically rare (once per century in the recent past) are projected to occur frequently (at least once per year) at many locations by 2050 in all emission scenarios, especially in tropical regions. The increasing frequency of high water levels can have severe impacts in many locations depending on exposure. Sea level rise is projected to continue beyond 2100 in all emission scenarios. Extreme sea levels and coastal hazards will be exacerbated by projected increases in tropical cyclone intensity and precipitation, and projected changes in waves and tides vary locally in whether they amplify or ameliorate these hazards.

What are the risks for ecosystems and humans? As summarized in B5-6, and B8-9, the changes are likely to be wide-ranging. A decrease in global biomass of marine animal communities, their production, and fisheries catch potential, as well as a shift in species composition, are projected over the 21st century from the surface to the deep seafloor under all emission scenarios. Ocean acidification, oxygen loss, and reduced sea ice extent, as well as non-climatic human activities, have the potential to exacerbate these warming-induced ecosystem impacts.

Risks of severe impacts on biodiversity, structure and function of coastal ecosystems are projected to be higher for elevated temperatures under high compared to low emissions scenarios in the 21st century and beyond. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. The capacity of organisms and ecosystems to adjust and adapt is higher at lower emissions scenarios. For sensitive ecosystems such as seagrass meadows and kelp forests, high risks are projected if global warming exceeds 2°C above pre-industrial temperatures, combined with other climate-related hazards. Warm-water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C.

Future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine-resource-dependent communities. Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being.

Increased average and extreme sea level, alongside ocean warming and acidification, are projected to exacerbate risks for human communities in low-lying coastal areas under higher emission scenarios, causing greater harm and presenting greater challenges than low emission scenarios. Ambitious adaptation including transformative governance is expected to reduce risk, but with context-specific benefits.

The report also includes a very relevant section regarding how to implement responses to these observed and predicted changes to the ocean and cryosphere (Section C). Much of this section is in the realm of "policy" and thus is not my purview here. However, virtually all of the implementation activities discussed in the report will strongly benefit, and have their chance of success greatly elevated, by increased scientific understanding of the ocean. I argue here that the overall approach of making bold and innovative investments in the ocean observation enterprise will be the most impactful way to achieve this goal.

For example, this section of the report discusses adaptation strategies and notes that “people with the highest exposure and vulnerability are often those with the lowest capacity to respond.” I note, however, that investment in ocean science, engineering, and technology could help reduce this vulnerability. Coastal restoration, decreasing coastal pollution, managed retreat of our land-based communities and infrastructure, and all the other options being discussed, will benefit from enhanced ocean observations and an improved predictive capability.

Research Highlight: The ocean twilight zone

The ocean’s mesopelagic, or twilight zone, is a poorly understood region of the ocean between 200 and 1,000 meters (650 and 3,300 feet) where sunlight is barely a glimmer and insufficient to support photosynthesis. Nevertheless, it is teeming with life—some estimates put the biomass of the twilight zone at 10 times that of the rest of the ocean combined. As a result, many commercial fishing interests are beginning to target the region as a way to meet demand for fishmeal drive by aquaculture.

The twilight zone is also a critical part of the biological carbon pump, which helps move carbon from sunlit surface waters, where photosynthesis turns carbon dioxide into organic carbon, down to deep waters, where it may be stored for hundreds or thousands of years. WHOI’s [Ocean Twilight Zone](#) effort, funded by the Audacious Project at TED, is attempting to advance knowledge of the mesopelagic in an effort to provide policy-makers with the knowledge they need to ensure sustainable long-term management of this vital marine resource that balances its value as a food source with its role in the global carbon cycle.

Key Findings from Other Recent Peer-Reviewed Reports

The IPCC report is receiving a great deal of attention, which I believe is appropriate given what we see going on around us and the tremendous importance of the ocean to the weather-climate system, both now and in the future. There have been many reports from the U.S. government, international bodies, NGOs, and academics on different aspects of the ocean system over the years, and summarizing them all is not appropriate for this testimony. However, two recent noteworthy ocean focused reports released in 2019 are summarized below, because they present different yet consistent perspectives on the role and impact on the oceans.

Sustaining Ocean Observations to Understand Future Changes in Earth's Climate
National Academies of Sciences Ocean Studies Board Workshop Report (2017)

<https://www.nap.edu/download/24919>

In 2017, the National Academies Ocean Studies Board convened members of the earth and ocean sciences community to consider processes for identifying priority ocean observations that will improve understanding of the Earth's climate processes and the challenges associated with sustaining these observations over long time frames, as well as approaches for overcoming these challenges. Their findings are very insightful, and I highlight some of the most salient ones in Recommendations below. I will also present a more thorough summary of this report's findings as an appendix to this testimony.

Ocean Deoxygenation: Everyone's problem

International Union for Conservation of Nature (2019)

<https://portals.iucn.org/library/sites/library/files/documents/2019-048-En-Summ.pdf>

Working with 67 scientific experts representing 51 institutes in 17 countries, this report presents what to my knowledge is the largest peer-reviewed study conducted so far on ocean deoxygenation. Ocean deoxygenation is occurring at all depths due to lower solubility of oxygen in warmer waters, stronger vertical stratification (steeper temperature gradient) inhibiting diffusion of oxygen from the surface to the deep ocean, and more sluggish deep circulation that reduces oxygen supply to deep waters.

Alongside this, increased nutrient inputs to the ocean through river runoff and from the atmosphere are promoting algal blooms, increasing oxygen demand and causing development of hundreds of coastal hypoxic (dead) zones in the ocean as well as intensification of naturally formed low-oxygen zones. According to the report:

- The global ocean oxygen inventory has decreased by about 2 percent over the period 1960 to 2010. One other specific study notes that in some tropical areas the oxygen content has decreased by 40 percent over the past 50 years (<https://www.scientificamerican.com/article/the-ocean-is-running-out-of-breath-scientists-warn/>).
- Model simulations project a decline in the dissolved oxygen inventory of the global ocean of 1 to 7 percent by the year 2100, caused by a combination of warming-induced decline in oxygen solubility and reduced ventilation of the deep ocean.

- Longer-term oxygen trends caused by climate change are masked by oxygen variability on a range of different spatial and temporal scales.
- The decline in the oceanic oxygen content can affect ocean nutrient cycles and the marine habitat, with potentially detrimental consequences for ecosystems, dependent people and coastal economies.
- Ocean oxygen loss is closely related to ocean warming and acidification caused by increasing carbon dioxide driven by anthropogenic emissions, as well as biogeochemical consequences related to anthropogenic fertilization of the ocean; hence a combined effort investigating the different stressors will be most beneficial to understand future ocean changes.
- It is predicted that there will be distinct regional differences in the intensity of oxygen loss as well as variations in ecological and biogeochemical impacts. There is consensus across models that oxygen loss at mid and high latitudes will be strong and driven by both solubility reductions and increased respiration effects.

The Ocean as a Solution for Climate Change: 5 Opportunities for Action
High Level Panel for a Sustainable Ocean Economy (2019)

(http://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf)

The “High Level Panel” is a unique group of world leaders from around the globe committed to developing, catalyzing and supporting solutions for Ocean health and wealth in policy, governance, technology and finance. The report identifies five ocean-based climate action areas that can help in the fight against climate change. Full implementation of these ocean-based climate solutions could deliver one-fifth (up to 21 percent) of the annual greenhouse gas emissions cuts the world needs by 2050 to keep global temperature rise below 1.5 degrees Celsius. These are:

- *Ocean-based renewable energy*: Reduce barriers to scaling up offshore wind (fixed and floating turbines) and invest in new, innovative ocean-based energy sources such as floating solar photovoltaics, wave power, and tidal power.
- *Ocean-based transport*: Implement available technologies to increase energy efficiency now (e.g., improved hull design), and support the development of

low-carbon fuels as part of a broader decarbonisation of ocean industries and energy supply chains, including port facilities. Start with decarbonising the domestic fleet, such as coastal ferries.

- *Coastal and marine ecosystems*: Conserve existing “blue carbon” ecosystems (mangroves, seagrass beds, and salt marshes) to prevent further release of GHG emissions and scale up restoration efforts. Expand farmed seaweed as an alternative fuel and feed source.
- *Fisheries, aquaculture, and dietary shifts*: Reduce the emissions intensity of fisheries and aquaculture operations through optimising wild catch and shifting to low carbon feed options. Shift diets toward low carbon marine sources such as sustainably harvested fish, seaweed, and kelp as a replacement for emissions intensive land-based sources of protein.
- *Carbon storage in the seabed*: Invest in the research necessary to minimize environmental impacts of long-term storage of carbon in the seabed and remove regulatory and economic barriers.

In addition, The High Level Panel has commissioned a series of “Blue Papers” (<https://www.oceanpanel.org/blue-papers>) to explore pressing challenges at the nexus of the ocean and the economy. These Blue Papers will summarize the latest science, and state-of-the-art thinking about innovative ocean solutions in technology, policy, governance, and finance realms that can help to accelerate a move into a more sustainable and prosperous relationship with the ocean. Sixteen Blue Papers are in development and will be released with regular cadence between November 2019 to June 2020.

I note that each of the above climate “action areas” will benefit greatly from increased investment by the U.S. Government in the overall enterprise of ocean science, engineering, and technology in the context of ocean observations. In the next section of my testimony here, I will present some of these investments to date, and point out their successes in the context of further future opportunities.

Research Highlight: Ensuring the future of coral reefs in a warming ocean

Coral reefs occupy barely one percent of Earth's surface, yet they host more than one-quarter of marine life, protect communities and coastlines from waves and storms, and support almost 1 billion people. They are the tropical ocean's most valuable ecosystem, yet their future is highly uncertain. Climate change, particularly ocean warming, has already killed thousands of square kilometers of reef around the globe and extinction potentially looms as ocean temperatures rise unabated.

Newly discovered "Super Reefs" have the ability to survive in a rapidly warming ocean. With tools and technologies that include autonomous underwater vehicles, hydrodynamic modeling, and genomic analysis, a team that includes Anne Cohen (WHOI) plus collaborators at Stanford and The Nature Conservancy are locating these extraordinary places, and uncovering their secrets. Some are genetically adapted to resist extreme heat; others are cooled by natural oceanographic processes. Super Reefs that survive will naturally restock neighboring regions and will provide the source to restock reefs worldwide.

Major Existing Ocean Observing Programs of Interest

In recent decades, the U.S. Federal Government has committed to supporting the transitional development of ocean observing systems. Many of these are also contributed to by the international community, either via direct pairing or by our international colleagues responding to U.S. leadership and spinning up parallel programs. Although the U.S. has much to be congratulated for, we are now facing the realization that in order to develop the baseline scientific knowledge to address societally relevant questions over societally relevant time frames, we need vastly improved data coverage, data interpretation approaches and techniques, and a workforce unlike anything that currently exists. Therefore, it is important to acknowledge and describe some of the successes that the U.S. has led, to help frame the discussion of immediate and future needs. I need to emphasize that the below four discussions are representative, and not an exhaustive listing.

Argo

The Argo Program is a global array of 3,800 free-drifting instruments, initially spaced about every 3° of latitude and longitude, including in the seasonal sea-ice zone and marginal seas. The floats move up and down in the water from the sea surface to 2,000 meters (about 1.2 miles, vertically) every 10 days and collect up to 1,000 measurements of temperature, salinity, and depth. Argo provides the first ever global-scale, all-weather, all-season subsurface observations of the oceans.

Before Argo, the temperature and salinity of the subsurface oceans could only be measured from ships or fixed-point moorings. As a result, these measurements were nowhere near as globally distributed as Argo provides. Since the first Argo float deployments in late 1999, over 1.6 million profiles have been collected which more than doubles the number from research vessels during all of the 20th century. Each year, Argo adds more than 120,000 new profiles. Argo is now the preeminent source of information about the climatic state of the oceans.

Pilot efforts to enhance the core Argo Program are in various stages of development. Some of these enhancements include floats sampling deeper than 2,000 meters (Deep Argo, below), carrying additional sensors to measure biogeochemical parameters (BGC Argo, below), and increased coverage in polar regions and in areas of the ocean with high variability (Polar Argo, below).

Today, Argo provides an unprecedented dataset that is freely available for researchers studying the temperature, salinity, and circulation of the global oceans and how these change over periods ranging from days to decades. These estimates allow the development of climate indicators such as the recent changes in ocean heat content and sea level. Argo data are also vital for climate and ocean forecasting services (from days to years), which are used for many applications such as search and rescue, crop management, and disaster preparedness.

Deep Argo: A new generation of autonomous floats called Deep Argo will sample the full ocean depth and volume. Deep Argo float models include the Deep SOLO and Deep APEX capable of reaching 6000 meters, and the Deep ARVOR and Deep NINJA designed to sample to 4000 meters. Regional Deep Argo arrays in the Southwest Pacific Basin, South Australian Basin, Australian Antarctic Basin, and North Atlantic Ocean are leading the way forward to implement a standing Deep Argo array of 1,228 floats. An exciting transition to systematic full-depth global ocean observations is happening.

Biogeochemical-Argo: (BGC-Argo) is the extension of the Argo array of profiling floats to include floats that are equipped with biogeochemical sensors for pH, oxygen, nitrate, chlorophyll, suspended particles, and downwelling irradiance. A BGC-Argo array would enable direct observation of the seasonal- to decadal-scale variability in biological productivity, the supply of essential plant nutrients from deep-waters to the sunlit surface layer, ocean acidification, hypoxia, and ocean uptake of carbon dioxide. It would extend ocean color remote sensing observations deep into the ocean interior and throughout the year in cloud covered areas. The system would drive a transformative shift in abilities to observe and predict the impact of climate change on ocean ecology, metabolism, carbon uptake, and marine resource modeling.

Polar Argo: Argo floats have been successfully deployed in the seasonal ice zone of both poles over the past decade. More than 45,000 profiles south of 60°S have been collected since 2001. Advances in float technology including two-way communications through the Iridium satellite network, software modifications (ice avoidance algorithm and the ability to store winter profiles) and improved hardware have resulted in ice floats surviving multiple winters under sea ice. In recognition of the successful deployment of floats into the seasonal ice zone and the desire for a truly global Argo data system, the Argo Steering Team has recommended that core Argo be extended beyond 60°S and 60°N.

In order to advance the Argo program nationally and globally, the community must find additional resources to ensure the sustainability of the existing array—which experienced funding reduction in the U.S. in 2019—and support for expansion into Deep, BCG, and the high latitudes floats.

Research Highlight: Reading the ocean's memory

A 2019 analysis by Geoffrey Gebbie (WHOI) and Peter Huybers (Harvard) of thousands of measurements from the HMS Challenger expedition, the scientific voyage that sailed around the globe from 1872 to 1876. Their work revealed that the deep Pacific Ocean is still feeling the effects of the Little Ice Age that chilled surface waters between the 16th and 19th centuries. Although the decrease in temperature is small, the volume over which it is occurring is extremely large and highlights the long climate memory of the ocean.

A lack of sustained observations from the deep ocean means the role that the region plays in the climate system has likely been underestimated. It also forced researchers to look to the historical record for insight. They found that the deep Pacific underwent a net cooling over the 20th century, despite warming almost everywhere else. Basic climate questions like the role of the deep ocean will remain unanswered with sufficient precision until more sustained observations of basic parameters like temperature are gathered and incorporated into state-of-the-art models to reduce predictive uncertainty.

Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP)

Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 kilometers (which represents 52 percent of global ocean volume not sampled by Argo and other profiling floats).

Global hydrographic surveys have been carried out approximately every decade since the 1970s through research programs such as GEOSECS, WOCE, JGOFS, and CLIVAR. However, global repeat hydrography has lacked formal global organization since the end of WOCE and this has led to a lack of visibility for hydrography in the global observing system as well as a significant decrease in the number of trans-basin sections carried out by some countries. More importantly, the lack of international agreements for implementation of hydrographic sections has led to disparate data sharing policies, duplication of some sections, and sections being carried out without the full suite of core variables.

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) brings together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of ocean interior data, and coordinates a network of globally sustained hydrographic sections as part of the global ocean/climate observing system including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems.

GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast and full depth (top to bottom), with global measurements of the highest required accuracy to detect these changes. The GO-SHIP principal scientific objectives are: (1) understanding and documenting the large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of how a future ocean will increase in dissolved inorganic carbon, become more acidified and more stratified, and experience changes in circulation and ventilation processes due to global warming and altered water cycle. The GO-SHIP program provides a vitally required baseline of data necessary for other programs, such as Argo, to use as a core global reference source. .

Long Term Ecological Research (LTER) Network

The Long Term Ecological Research (LTER) Network was founded in 1980 by the National Science Foundation with the recognition that committing to long-term research could help unravel the principles and processes of ecological science, which frequently involves long-lived species, legacy influences, and rare events. As policymakers and resource managers strive to incorporate reliable science in their decision making, the LTER Network works to generate and share useful and usable information.

Thus, LTER's mission is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide. Sites that support significant ocean-focused research include Beaufort Lagoons, California Current Ecosystem, Florida Coastal Everglades, Georgia Coastal Ecosystems, Moorea Coral Reef, Northeast Shelf, Palmer Antarctica, and Virginia Coast Reserve. Recent additions to the LTER coastal suite are the Northern Gulf of Alaska and the Northeast U.S. Shelf sites. The latter site leverages other National Science Foundation (NSF) investments in the Martha's Vineyard Coastal Observatory (MVCO) and the Ocean Observatories Initiative (described below).

Ocean Observatories Initiative (OOI)

The NSF-funded Ocean Observatories Initiative (OOI) is an integrated infrastructure program composed of science-driven platforms and sensor systems that measure physical, chemical, geological, and biological properties and processes from the seafloor to the air-sea interface. The OOI network, which is operated by WHOI, the University of Washington, Oregon State University, and Rutgers University, was designed to address critical science-driven questions that will lead to a better understanding and management of our oceans, enhancing our capabilities to address critical issues such as climate change, ecosystem variability, ocean acidification, and carbon cycling in key locations of the ocean and seafloor in the Northern Hemisphere.

The OOI has transformed research of the oceans by integrating multiple scales of globally distributed marine observations into one observing system and allowing for that data to be freely downloaded over the internet in near-real time. The OOI intends to deliver data and data products for a 25-year-plus time period within an expandable architecture that can meet emerging technical advances in ocean science. Building on last century's era of ship-based expeditions, recent technological leaps have brought us to the brink of a sweeping transformation in our approach to ocean research – the focus on expeditionary science is shifting to a permanent presence in the ocean. As technological advances continue over the lifetime of the OOI, developments in sensors, computational speed, communication bandwidth, internet resources, miniaturization, genomic analyses, high-definition imaging, robotics, and data assimilation, modeling, and visualization techniques will continue to open new possibilities for remote scientific inquiry and discovery.

Research Highlight: Engaging the fishing community

Waters off the southern New England coast teem with marine life and support an active commercial fishery. These waters have been historically fished since before the arrival by the Pilgrims, and served as the initial stimulus for Europeans to explore North America. But in recent years fishermen have noticed conditions in the region are changing to an extent and in a way not seen previously. In particular, they have seen rising water temperatures, changing currents, and the arrival of new species. This led Glen Gawarkiewicz (WHOI) to more formally incorporate their observations into his studies of the shelfbreak, where coastal and deep-ocean waters mix.

In 2014, he teamed up with the Commercial Fisheries Research Foundation (CFRF) to create the Shelf Research Fleet, which is made up of commercial fishing vessels that fish in or transit through waters off the Northeast Coast. The partnership between scientists and commercial fishermen has proven to be a cost-effective way to collect much-needed scientific data from a critical part of the ocean also occupied by elements of OOI and LTER. The project also has contributed significantly to a more holistic approach to science, in which different constituencies “coproduce” data and observations. Fishermen, for example, reported some of the first signs of a 2016-2017 marine heatwave that reached 6°C above average at its peak, when boats caught Gulf Stream flounder and juvenile black bass—warm-water fish not common in northern waters.

Relevance of SROCC findings for the U.S. Economy and National Security

The findings of the IPCC SROCC report findings have direct and significant relevance to the U.S., clearly demonstrating the impact of ocean and climate on our economic and national security, as well as on the health and productivity of marine ecosystems that provide much of our sustenance and societal well-being. Our collective capacity to understand, assess, adapt to and mitigate the impacts of the potentially profound changes that will accompany a rapidly warming climate will require much better operational modeling and forecasting of both large scale processes—heat, carbon, freshwater budgets—and those that influence our daily lives, including weekly, sub-seasonal, seasonal, and annual weather forecasts, fisheries stock assessments, marine biodiversity, and extreme weather events. There are also very real national

security implications associated with having improved knowledge of the ocean environment as we face challenges from adversaries in the undersea domain.

Economic Security

The U.S. is a maritime nation, bounded by ocean on three coasts and the Great Lakes to the north. We have over 95,000 miles of coastline, and our Exclusive Economic Zone (EEZ) is 11,351,000 km² or 4,383,000 square miles, larger than the nation's continental land area. According to NOAA, coastal counties of the U.S. are home to over 126 million people, or 40 percent of the nation's total population, of which approximately 40 percent fall into an elevated coastal hazard risk category. The risk management company AIR Worldwide (<https://www.air-worldwide.com>) estimates that, based on maximum modeled storm surge extent, the total value of residential and business insurable property in ZIP codes on the East and Gulf Coasts potentially impacted by storm surge is \$17 trillion. This large value is actually a minimum estimate, as it does not include public infrastructure such as roads, ports, railways, wastewater and drinking water facilities, and military bases, or uninsured property.

The changing climate also has implications for the commercial and recreational fishing industries, whose combined total sales in 2016 was \$212 billion according to the National Marine Fisheries Service. And while more difficult to quantify, there are also potential impacts on the U.S. ocean-based tourism and recreation, which according to NOAA contributes approximately \$124 billion in gross domestic product to the national economy each year. The 2018 National Climate Assessment further puts the total GDP from shore-adjacent counties at \$7.2 billion, nearly half of the total U.S. GDP for 2013 (<https://nca2018.globalchange.gov/chapter/8/>). These indeed are large and significant contributors to the U.S. economy's overall well-being and long-term growth and viability.

Returning to the theme of my testimony, I will reiterate the importance of the ocean and coastal observing enterprise's role supporting efforts to improve our capacity to predict and refine knowledge of the timing, scale, and range of anticipate changes. Improved ocean and coastal observations and monitoring will continue to help shape and guide improvements in operational modeling and forecasting. These modeling improvements, including greater quantification and refinement of the value of natural resources, which will in turn drive advances in risk assessment and risk management capabilities. The improved risk data and modeling forecasts will greatly assist public and private sector decision makers, as well as citizens, make the necessary cost/benefit assessments and tradeoffs that will accompany personal, business, and public policy decisions that will have significant short- and long-term fiscal, social, environmental, and military implications. For example, insurance and re-insurance giants such as Swiss Re are

deploying sophisticated business approaches to the problem given that the global re-insurance industry is managing total assets of about \$30 trillion (roughly three times the size of China's economy

(<https://www.swissre.com/risk-knowledge/mitigating-climate-risk.html>).

Research Highlight: Forecasting rainfall from sea-surface salinity

Sea-surface salinity is a natural indicator of precipitation and evaporation in the ocean, a key part of the global water cycle. Low salinity signals large inputs of freshwater from rainfall have occurred and high salinity indicates elevated evaporation transferring water from the ocean to the atmosphere. Over a career of studying the global water cycle, Ray Schmitt (WHOI) developed a method of forecasting precipitation in places like the U.S. Midwest and African Sahel based on sea-surface salinity patterns.

His work went largely unrecognized by traditional funding sources, so he turned to the Bureau of Reclamation's Sub-Seasonal Forecast Rodeo, in which teams worked to provide the best three-to-six-week precipitation forecasts over a year-long competition. Schmitt and his sons used sea-surface salinity data gathered by NASA, NOAA, and other sources, combined with artificial intelligence techniques, to outperform all other competitors—including professional forecasting companies and a climate model developed by NOAA. This work is an excellent example of how distant ocean processes affect weather even in the interior of continents, and speaks to how ocean observations of basic parameters such as salinity can deliver key information back for societal benefit

National Security and Defense

Finally, improved awareness of ocean processes through advances in ocean observations and modelling is critical to our national security in light of the renewed Great Powers Competition with China and Russia, particularly in the undersea domain. There are issues both within our EEZ as well as in far-flung ocean regions in which the benefits of ocean observing will be immediately felt. Military strategy is strongly influenced by situational awareness and those warfighters on the side with better knowledge of the seascape will be better positioned to take advantage of this information in times of peace as well as in the event of a conflict.

A nuance to some but of immediate practical importance to our national defense is the fact that because the ocean environment has changed significantly over the past few

decades some of the historical ocean data is obsolete. There is an irony here. We have a strong understanding of the past conditions in key areas, which benefits our comparisons to the modern ocean and means we can identify where and what type of measurements are needed to better constrain uncertainty in our understanding of climate change. At the same time, these changes limit the operational capabilities of our systems of national defense.

For example, consider underwater acoustics—the process by which we monitor the presence of submarines and other underwater objects. Acoustical properties are strongly influenced by changes in water density, which is dictated primarily by heat and salinity as well as the presence of biology, such as plankton and fish. Any improvement in the collection of undersea data will help make the ocean more transparent to our military, allowing them to better monitor the position of the underwater assets of our competitors, as well as position our own assets where they are less likely to be observed. This is why the U.S. Navy has historically been at the forefront in the development and deployment of certain types of advanced underwater technologies, supported by the Office of Naval Research (ONR) and other defense entities. Partnerships between ONR and academia have yielded exceptional benefits in this arena over the past 80 years.

Recommendations

Sustaining Ocean Observations to Understand Future Changes in Earth's Climate **National Academies of Sciences Ocean Studies Board Workshop Report (2017)**

As I noted earlier in the testimony, in 2017, the National Academies Ocean Studies Board convened members of the earth and ocean sciences community to consider processes for identifying priority ocean observations that will improve understanding of the Earth's climate processes and the challenges associated with sustaining these observations over long time frames, as well as approaches for overcoming these challenges. Their conclusions are very insightful, and, in addition to the following highlight of some of the most salient ones, I have provided a more thorough summary of the report's key findings as an appendix to this testimony.

First, it is helpful to summarize some basic ocean observation facts:

- Ocean observations are made using both satellite and in situ (in water) instrumentation.
- In situ observations are carried out using fixed and mobile platforms such as tide gauges, data buoys, moorings, ship-based observations, profiling floats, ocean gliders, and surface drifters. This is a representative list only.
- Priority ocean variables observed for climate are sea state, ocean surface stress, sea ice, sea surface height, sea surface temperature, subsurface temperature, surface currents, subsurface currents, sea surface salinity, subsurface salinity, ocean surface heat flux, and dissolved inorganic carbon.
- The ocean observing enterprise is an end-to-end system built on engineering, operations, data management, information products, and the associated human capabilities, which are supported by the planning and governance by international coordination entities and by regional and national agencies.

The Value of Sustained Observations

In the face of a changing climate, society will increasingly face complex decisions about how to adapt to and mitigate the adverse impacts of climate change such as droughts, sea-level rise, ocean acidification, species loss, changes to growing seasons, and stronger and possibly more frequent storms. To make informed decisions, policy makers will need information that depends on understanding the dynamics of the planet's climate system. Because these dynamics will evolve as the climate warms, the ability to anticipate and predict future climate change will depend on ongoing observations of key climate parameters to tune and enhance models. Sustained collection of ocean observations over years, decades, and centuries monitoring the Earth's main reservoirs of heat, carbon dioxide, and water will provide a critical record of long-term change and variability over multiple timescales. Sustained observations of environmental variables –including essential ocean variables—are thus essential to advance understanding of the state of the climate system now and in the future.

Highlights of Report Findings

Progress and Benefits

We need to start by recognizing the progress that has been made by the current ocean observing system and the benefits it has provided. Our increasing awareness of the major role the ocean plays in climate processes is due largely to ongoing observation programs supported by governments in the U.S. and abroad, which are focused on improving our understanding of the planet's heat, carbon and freshwater budgets, and

the many subprocesses entrained within them. NOAA, NSF, NASA, and the U.S. Navy are the core supporters of ocean and coastal observing systems, but there are additional contributors across the federal agencies. This system contributes not only to our understanding of climate variability and change, but also to a wide variety of other services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. As noted previously, this understanding of climate variability and change and other services underpins national defense, economic, and social policy decisions.

We must also recognize that the U.S. ocean observation enterprise is part of a broader collaborative and cooperative Global Ocean Observing System (GOOS). The GOOS effort is guided by the Framework for Ocean Observing, which helps identify priority observation, known as Essential Ocean Variables and requirements for their precision, frequency, spatial resolution. There are opportunities to increase the spatial coverage of observation through increased coordination and sharing of resources, as well as leveraging GOOS to enhance capacity building and support for observations in other nations.

Challenges

While the current U.S. ocean observing system is functional and has made considerable advances over the past 10 years, it is woefully undersized and is often inadequately funded to fulfill existing information demands, much less future demands. The workshop report identifies the absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership as two key challenges for sustained U.S. ocean observing, which inhibit effective coordination and multiyear investments in the many components of the observing system.

These weaknesses are evidenced by recent challenges experienced across the observing system. This includes relatively flat funding for “Sustained Ocean Observations and Monitoring” program within NOAA Oceanic and Atmospheric Research (OAR). This program supports funds a range of in-situ global observing capabilities, including the Argo and Deep Argo programs, the Tropical Pacific Observing System, moored and drifting buoy arrays and global reference systems, gliders, and tide gauges. Collectively, these programs are critical to our nation’s environmental observation system. The in situ ocean data these programs provide are essential to ground truthing satellite-based ocean observations. The program also provides critical ocean observations in the equatorial Pacific Ocean necessary to understand and forecast El Niño events, which have major economic and societal impacts in the U.S. and worldwide

Over the past decade, all elements of the NOAA program have experienced a substantial reduction in deliverables and/or degradation of services impacting operational activities and limiting scientific advances important to understanding and improving our weather and climate forecast systems. For example, in FY2019, Argo annual float deployments dropped well below its 350-unit target, to 273 units, which, if repeated in future years, will result in significantly reduced global coverage for the program.

Similar funding challenges are impacting the federal research fleet and its capacity to support ocean and coastal observations. The report finds that research vessels are indispensable to the ocean observing system and require long-term planning and investment. It states that maintenance of a capable fleet of research vessels is an essential component of the U.S. effort to sustain ocean observing. However, NOAA struggles to keep its only global class vessel operating in order to support its ocean observation missions. NSF's academic fleet is similarly fiscally challenged, particularly in supporting the cost of annual deployment and replacement of key global reference systems buoys, particularly in the southern polar latitudes, an area where there is limited understanding of what is believed to be the location of significant transfer of heat between the ocean and atmosphere.

In addition, the report finds the ocean observing program has been further impeded in its ability to adopt new advanced technologies, transition research observations to operations, and address new, high-priority observing opportunities. The limited investment in advancing technological capabilities is a challenge that, if addressed, will yield significant returns over the lifetime of sustained observing platforms through development of more robust, efficient and hopefully less costly sensors and platforms. The potential for autonomous underwater vehicles to collect large amounts of data is immense; however, the deployment of fleets of such vehicles requires major advances in software as well as underwater communications, for which funding is often difficult to secure. This situation is further impacted by challenges related to limited professional rewards or career incentives at research institutions and laboratories to ensure intergenerational succession of scientists, engineers, and technical staff, a reminder that workforce development is an often overlooked, but critical element of the systems long term success.

It is difficult to overstate the importance of establishing and sustaining databases of essential ocean variables. These databases allow scientists to observe changes over long periods of time and across wide areas or, as is more important in the ocean, over

vast volumes. Doing so greatly improves our understanding of the underlying processes and the rate at which change is occurring in various systems. It also helps differentiate between natural variability, such as the Pacific and Atlantic decadal oscillations, and those influenced by human activities. When long-term observations are halted or broken, the discontinuity in the database can never be rectified –you cannot go back in time to collect data—and this compromises the reliability of models and forecasts based on this data. Years and decades in the future, scientists will rely on, and carefully scrutinize the quality of the data we collect today, so one of our core obligations is to identify the proper variables to observe and monitor, and maintain the integrity of these datasets for future use. Therefore, the report emphasizes the importance of planning end-to-end scope of expenses associated with observing programs, including appropriate logistical planning.

Finally, the report raising awareness of the importance and value of sustained ocean climate observations could increase support for the observing system from multiple sectors, including philanthropic organizations. This opportunity will be one area of focus of the second phase of the study that is scheduled to start later this month where new models or approaches to sustained ocean observing will be pursued. Additionally, the global ocean observing community convened for its decadal gathering last September in Hawaii (<http://www.oceanobs19.net>) and their recommendations for advancing the global system are expected to be refined and released later this year.

Research Highlight: Australia and the Indian Ocean

Australia is burning, but to understand how the relentless heat, blazing wildfires, and dry conditions on land have reached such extremes, Caroline Ummenhofer (WHOI) and Gerald Meehl (National Center for Atmospheric Research) is looking to the ocean. Ummenhofer studies how ocean patterns in the Indian Ocean influence rainfall and extreme events—such as droughts and floods—on adjacent landmasses.

In particular, Ummenhofer is looking to the Indian Ocean as a key driver of Australian rainfall variability. Her work has shown that unusual conditions occurred in the Indian Ocean during all major prolonged 20th century drought episodes in Australia. Among these drivers is a weather pattern called the Indian Ocean Dipole (IOD)—a phenomenon similar to the Pacific Ocean’s El Niño—which can cause see-saw-like variations in sea surface temperatures across the eastern and western Indian ocean every 3-6 years on average. A record Indian Ocean dipole event occurred during the second half of 2019, during which stronger monsoon winds in the eastern Indian Ocean pushed warm waters to the western Indian Ocean. The warm water brought heavy rainfall and floods to Africa, while Australia and Indonesia experienced reduced cloud cover and moisture.

The Ocean Observation Enterprise

As I stated at the outset of this testimony, and as I hope is bolstered by the information presented here, *my singular recommendation relates to the need for a significantly enhanced ocean observation enterprise across ocean science disciplines, geographic regions, and temporal and spatial scales in the ocean.* The societal value of the data gathered by such ocean observations is ultimately related to its relevance to policy-makers in formats that clearly indicate the level of scientific confidence in its credibility and the clarity of any subsequent analysis and its ability to communicate trends and implications.

Climate impacts are appearing more rapidly and widely than anticipated, including in the ocean, which has increased the urgency for near real-time, ocean and coastal basin-wide observations (writ large, including associated infrastructure). Thus, this ocean observation enterprise must be done in partnership with private industry and public policymakers who are charged with making decisions that have long-term fiscal implications, and who are in need of improved certainty/confidence in climate information/data to facilitate risk assessment and risk management at the local,

regional, national and international level. The limited availability of ocean data is a significant factor hampering our ability to improve the predictive capabilities of climate and weather models, which is key to helping identify solutions, and quantify risk, that can scale to meet the magnitude of the challenges associated with a rapidly changing climate.

Concluding Thoughts

As I hope has become clear from this testimony, there are many implications of the SROCC report and associated challenges and needs in the ocean science community. However, the one that stands out the most, and one that is being focused on across on virtually all scientific disciplines in the ocean science community, is the need for improved observations such as I discuss throughout this testimony. This includes data collection, processing, and synthesis to facilitate its incorporation into models and predictions improvement, as well as driving new research avenues per the findings and recommendations of NAS Sustaining Ocean Observation 2017 workshop report I highlighted earlier in my testimony.

I also recommend that you read the testimony provided by Alexander (“Andy”) Karsner in September, 2019, before the House Financial Services Subcommittee on National Security, International Development, and Monetary Policy. Karsner is a well-known American technology entrepreneur, venture capitalist, and energy and environmental policy-maker and he spoke very cogently about the relationship between better data on climate change and national economic opportunities (<https://financialservices.house.gov/uploadedfiles/hhrg-116-ba10-wstate-karsnera-20190911.pdf>). I have highlighted some of his key points below, as I see them, because they emphasize the importance of and opportunities associated with climate data to the economic welfare of the nation. The essence of his recommendations are captured in his statement regarding the need to quantitatively measure the environment in order to better incorporate its value into the management and stewardship process:

“To manage and integrate the value of natural capital, we know we must measure it – not qualitatively and theoretically, but quantitatively and precisely. We can only truly manage what we can measure.... If we can measure and manage, then we also have the potential to continuously monitor and ultimately monetize the value of nature’s ecosystem services. This would enable the ultimate achievement: internalization of environmental externalities, and transparency for the systems that secure our health and well-being.”

Karsner's testimony is wide-ranging, addressing advances in artificial intelligence and machine learning in the financial sector, and notes that technological advances hold great promise not just for the future, but are ready now to be "widely deployed" through many sectors. It provides an interesting context to the springboard on which ocean science finds itself now, ready to vault into a future of innovative observations to modernize our understanding of the ocean.

Let me unequivocally state that there is a clear role for U.S. federal government investment in the collection of ocean and coastal data, one that private industry is very unlikely to every provide. Consider that the National Weather Service (NWS), which is a part of NOAA, plays the leading role in collecting and disseminating weather data, which is then used by private industry to develop value added products such as the plethora of weather apps on smartphones. The investment in the federal weather enterprise is huge, on the order of tens of billions of dollars, with the NWS annual budget used to operate and modernize the system. Although an excellent case of how government investment leads to private industry's success and to enhance public safety and quality of life, it is but one example of many. Unfortunately, given the importance of the ocean to climate and weather as described throughout my testimony, such investments in the ocean domain lag far behind their necessity.

While there is an existing ocean observing enterprise that includes ships, satellite sensors, buoys, drifters, floats, gliders, and autonomous underwater vehicles, technology development, high performance computers, and so on, it is a small fraction of the size of existing observing systems used for monitoring the land and atmosphere. For example, it is particularly problematic that the agency charged with supporting operational ocean observing systems—NOAA—has struggled for years to fund even the most basic programs and supporting infrastructure. The "Sustained Ocean, Coastal and Great Lakes Observations" budget line in NOAA OAR has essentially been level funded for the past 7 years (there is a \$1 million increase provided in FY 2020 appropriations). This has resulted in NOAA decreasing its support for the critical and valuable ARGO program, reducing support for key surface mooring that are reference sites used to calibrate and validate satellite data., Furthermore, NOAA has struggled to keep their research fleet operating, which has further limited the deployment of ocean observing assets.

The overall state of affairs of NOAA is a reflection on the ocean science community's lack of success in communicating to Congress, the Administration(s), and more importantly the taxpayer, about the need for a robust, modernized, and sustained ocean

and coastal observing system. It is my hope that the recent IPCC SROCC report will be the turning point where acknowledgement of the ocean's role in climate, and our economic and national security, will result in a commitment to forging an ocean observing enterprise that can fulfill the challenge of providing the data necessary to calibrate the rate of climate change, its impacts, and support decision making on adaptation and mitigation policies, in addition to ocean stewardship.

I close by noting that there are those who question whether we are losing the "race" between the speed of climate change and our ability to react. Regardless of how we are going to mitigate and/or adapt to the environmental changes we observe, Earth is still going to exist. Thus, the question is not really about a "race", but instead about how habitable will it be for our species. We live here, and it's the only planet I know that we can live on. Rather than winning or losing a race, we should look at whether we are peacefully coexisting with the environment, since it is the environment that is truly what sustains us. If we face an environment that is changing more rapidly than we anticipated, it does not mean we will lose the race, it means we will have to take more extreme actions to adapt.

It's easy to get discouraged, but that's where the science we do has a huge objective role to play. We are collecting unimpeachable data from our ocean, documenting the changes, comparing those to documented changes from the past, and then using that knowledge to inform our predictions for the future. With your continuing support for ocean science and observations, we can help meet future challenges with the best available information.

I thank you for the opportunity to appear before the Committee.

IPCC Special Report on the Ocean and Cryosphere in a Changing Climate
Summary for Policymakers
Key Findings

<https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/>

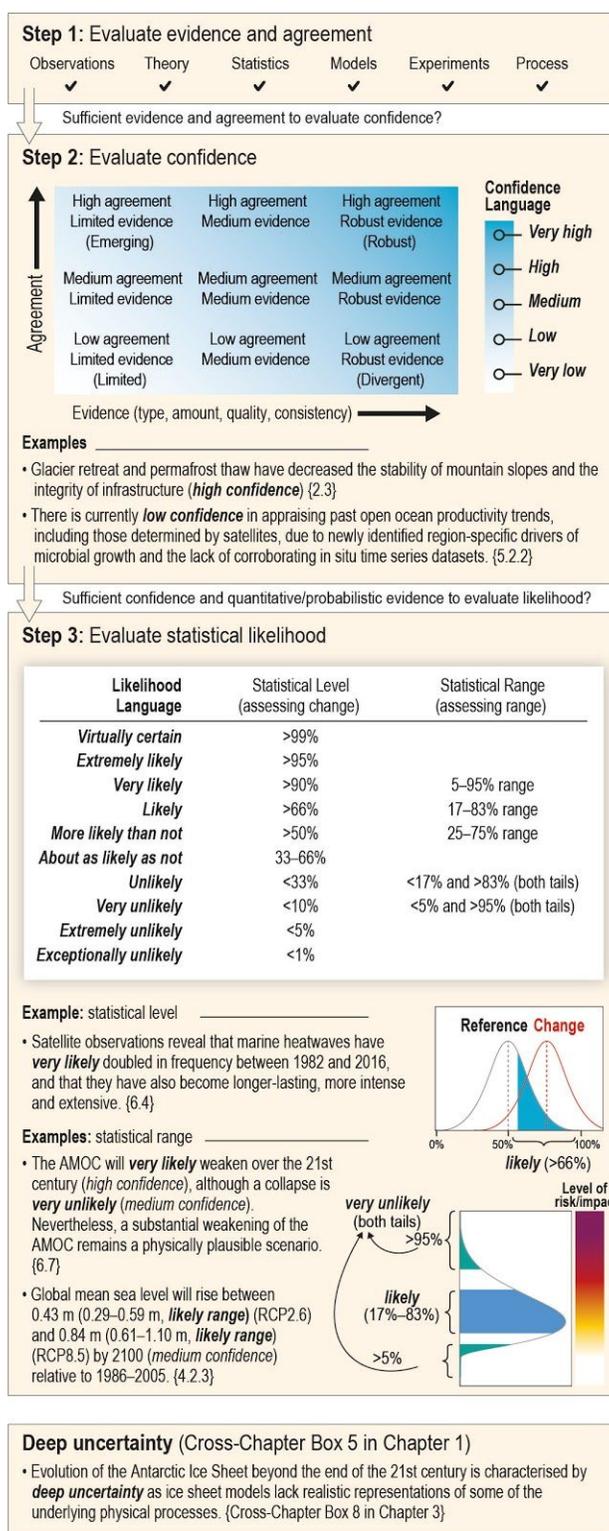
The importance of the ocean and cryosphere for people

All people on Earth depend directly or indirectly on the ocean and cryosphere. The global ocean covers 71% of the Earth surface and contains about 97% of the Earth's water. The cryosphere refers to frozen components of the Earth system.

Around 10% of Earth's land area is covered by glaciers or ice sheets. The ocean and cryosphere support unique habitats, and are interconnected with other components of the climate system through global exchange of water, energy and carbon. The projected responses of the ocean and cryosphere to past and current human-induced greenhouse gas emissions and ongoing global warming include climate feedbacks, changes over decades to millennia that cannot be avoided, thresholds of abrupt change, and irreversibility.

Human communities in close connection with coastal environments, small islands (including Small Island Developing States, SIDS), polar areas and high mountains⁷ are particularly exposed to ocean and cryosphere change, such as sea level rise, extreme sea level and shrinking cryosphere. Other communities further from the coast are also exposed to changes in the ocean, such as through extreme weather events. Today, around 4 million people live permanently in the Arctic region, of whom 10% are Indigenous. The low-lying coastal zone⁸ is currently home to around 680 million people (nearly 10% of the 2010 global population), projected to reach more than one billion by 2050. SIDS are home to 65 million people. Around 670 million people (nearly 10% of the 2010 global population), including Indigenous peoples, live in high mountain regions in all continents except Antarctica. In high mountain regions, population is projected to reach between 740 and 840 million by 2050 (about 8.4–8.7% of the projected global population).

In addition to their role within the climate system, such as the uptake and redistribution of natural and anthropogenic carbon dioxide (CO₂) and heat, as well as ecosystem support, services provided to people by the ocean and/or cryosphere include food and water supply, renewable energy, and benefits for health and well-being, cultural values, tourism, trade, and transport. The state of the ocean and cryosphere interacts with each aspect of sustainability reflected in the United Nations Sustainable Development Goals (SDGs).



All of the statements in the Special Report are assigned a quantitative statement of confidence or likelihood. This schematic demonstrates the IPCC usage of this calibrated language, with examples of confidence and likelihood statements from the *Special Report on the Ocean and Cryosphere in a Changing Climate*. More information is available in Chapter 1, Section 9.2.

A. Observed Changes and Impacts (Ecosystems and People)

Observed Physical Changes

A1. Over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers (very high confidence), reductions in snow cover (high confidence) and Arctic sea ice extent and thickness (very high confidence), and increased permafrost temperature (very high confidence).

A2. It is virtually certain that the global ocean has warmed unabated since 1970 and has taken up more than 90% of the excess heat in the climate system (high confidence). Since 1993, the rate of ocean warming has more than doubled (likely). Marine heatwaves have very likely doubled in frequency since 1982 and are increasing in intensity (very high confidence). By absorbing more CO₂, the ocean has undergone increasing surface acidification (virtually certain). A loss of oxygen has occurred from the surface to 1000 m (medium confidence).

A3. Global mean sea level (GMSL) is rising, with acceleration in recent decades due to increasing rates of ice loss from the Greenland and Antarctic ice sheets (very high confidence), as well as continued glacier mass loss and ocean thermal expansion. Increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal hazards (high confidence).

Observed Impacts on Ecosystems

A4. Cryospheric and associated hydrological changes have impacted terrestrial and freshwater species and ecosystems in high mountain and polar regions through the appearance of land previously covered by ice, changes in snow cover, and thawing permafrost. These changes have contributed to changing the seasonal activities, abundance and distribution of ecologically, culturally, and economically important plant and animal species, ecological disturbances, and ecosystem functioning. (high confidence)

A5. Since about 1950 many marine species across various groups have undergone shifts in geographical range and seasonal activities in response to ocean warming, sea ice change and biogeochemical changes, such as oxygen loss, to their habitats (high confidence). This has resulted in shifts in species composition, abundance and biomass production of ecosystems, from the equator to the poles. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning

(medium confidence). In some marine ecosystems species are impacted by both the effects of fishing and climate changes (medium confidence).

A6. Coastal ecosystems are affected by ocean warming, including intensified marine heatwaves, acidification, loss of oxygen, salinity intrusion and sea level rise, in combination with adverse effects from human activities on ocean and land (high confidence). Impacts are already observed on habitat area and biodiversity, as well as ecosystem functioning and services (high confidence).

Observed impacts on People and Ecosystem Services

A7. Since the mid-20th century, the shrinking cryosphere in the Arctic and high-mountain areas has led to predominantly negative impacts on food security, water resources, water quality, livelihoods, health and well-being, infrastructure, transportation, tourism and recreation, as well as culture of human societies, particularly for Indigenous peoples (high confidence). Costs and benefits have been unequally distributed across populations and regions. Adaptation efforts have benefited from the inclusion of Indigenous knowledge and local knowledge (high confidence).

A8. Changes in the ocean have impacted marine ecosystems and ecosystem services with regionally diverse outcomes, challenging their governance (high confidence). Both positive and negative impacts result for food security through fisheries (medium confidence), local cultures and livelihoods (medium confidence), and tourism and recreation (medium confidence). The impacts on ecosystem services have negative consequences for health and well-being (medium confidence), and for Indigenous peoples and local communities dependent on fisheries (high confidence).

A9. Coastal communities are exposed to multiple climate-related hazards, including tropical cyclones, extreme sea levels and flooding, marine heatwaves, sea ice loss, and permafrost thaw (high confidence). A diversity of responses has been implemented worldwide, mostly after extreme events, but also some in anticipation of future sea level rise, e.g., in the case of large infrastructure.

B. Projected Physical Changes

Projected Physical Changes

B1. Global-scale glacier mass loss, permafrost thaw, and decline in snow cover and Arctic sea ice extent are projected to continue in the near-term (2031–2050) due to surface air temperature increases (high confidence), with unavoidable consequences

for river runoff and local hazards (high confidence). The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond (high confidence). The rates and magnitudes of these cryospheric changes are projected to increase further in the second half of the 21st century in a high greenhouse gas emissions scenario (high confidence). Strong reductions in greenhouse gas emissions in the coming decades are projected to reduce further changes after 2050 (high confidence).

B2. Over the 21st century, the ocean is projected to transition to unprecedented conditions with increased temperatures (virtually certain), greater upper ocean stratification (very likely), further acidification (virtually certain), oxygen decline (medium confidence), and altered net primary production (low confidence). Marine heatwaves (very high confidence) and extreme El Niño and La Niña events (medium confidence) are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken (very likely). The rates and magnitudes of these changes will be smaller under scenarios with low greenhouse gas emissions (very likely).

B3. Sea level continues to rise at an increasing rate. Extreme sea level events that are historically rare (once per century in the recent past) are projected to occur frequently (at least once per year) at many locations by 2050 in all RCP scenarios, especially in tropical regions (high confidence). The increasing frequency of high water levels can have severe impacts in many locations depending on exposure (high confidence). Sea level rise is projected to continue beyond 2100 in all RCP scenarios. For a high emissions scenario (RCP8.5), projections of global sea level rise by 2100 are greater than in AR5 due to a larger contribution from the Antarctic Ice Sheet (medium confidence). In coming centuries under RCP8.5, sea level rise is projected to exceed rates of several centimetres per year resulting in multi-metre rise (medium confidence), while for RCP2.6 sea level rise is projected to be limited to around 1m in 2300 (low confidence). Extreme sea levels and coastal hazards will be exacerbated by projected increases in tropical cyclone intensity and precipitation (high confidence). Projected changes in waves and tides vary locally in whether they amplify or ameliorate these hazards (medium confidence).

Projected Risks for Ecosystems

B.4 Future land cryosphere changes will continue to alter terrestrial and freshwater ecosystems in high-mountain and polar regions with major shifts in species distributions resulting in changes in ecosystem structure and functioning, and eventual loss of globally unique biodiversity (medium confidence). Wildfire is projected to increase

significantly for the rest of this century across most tundra and boreal regions, and also in some mountain regions (medium confidence).

B5. A decrease in global biomass of marine animal communities, their production, and fisheries catch potential, and a shift in species composition are projected over the 21st century in ocean ecosystems from the surface to the deep seafloor under all emission scenarios (medium confidence). The rate and magnitude of decline are projected to be highest in the tropics (high confidence), whereas impacts remain diverse in polar regions (medium confidence) and increase for high emission scenarios. Ocean acidification (medium confidence), oxygen loss (medium confidence) and reduced sea ice extent (medium confidence) as well as non-climatic human activities (medium confidence) have the potential to exacerbate these warming-induced ecosystem impacts.

B6. Risks of severe impacts on biodiversity, structure and function of coastal ecosystems are projected to be higher for elevated temperatures under high compared to low emissions scenarios in the 21st century and beyond. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. The capacity of organisms and ecosystems to adjust and adapt is higher at lower emissions scenarios (high confidence). For sensitive ecosystems such as seagrass meadows and kelp forests, high risks are projected if global warming exceeds 2°C above pre-industrial temperature, combined with other climate-related hazards (high confidence). Warm water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C (very high confidence).

Projected Risks for People and Ecosystem Services

B7. Future cryosphere changes on land are projected to affect water resources and their uses, such as hydropower (high confidence) and irrigated agriculture in and downstream of high-mountain areas (medium confidence), as well as livelihoods in the Arctic (medium confidence). Changes in floods, avalanches, landslides, and ground destabilization are projected to increase risk for infrastructure, cultural, tourism, and recreational assets (medium confidence).

B8. Future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine resource-dependent communities (medium confidence). Long-term loss and degradation of marine ecosystems compromises the ocean's role in

cultural, recreational, and intrinsic values important for human identity and well-being (medium confidence).

B9. Increased mean and extreme sea level, alongside ocean warming and acidification, are projected to exacerbate risks for human communities in low-lying coastal areas (high confidence). In Arctic human communities without rapid land uplift, and in urban atoll islands, risks are projected to be moderate to high even under a low emissions scenario (RCP2.6) (medium confidence), including reaching adaptation limits (high confidence). Under a high emissions scenario (RCP8.5), delta regions and resource rich coastal cities are projected to experience moderate to high risk levels after 2050 under current adaptation (medium confidence). Ambitious adaptation including transformative governance is expected to reduce risk (high confidence), but with context-specific benefits.

C. Implementing Responses to Ocean and Cryosphere Change

Challenges

C1. Impacts of climate-related changes in the ocean and cryosphere increasingly challenge current governance efforts to develop and implement adaptation responses from local to global scales, and in some cases pushing them to their limits. People with the highest exposure and vulnerability are often those with lowest capacity to respond (high confidence).

Strengthening Response Options

C.2 The far-reaching services and options provided by ocean and cryosphere-related ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors. Integrated water management and ecosystem-based adaptation approaches lower climate risks locally and provide multiple societal benefits. However, ecological, financial, institutional and governance constraints for such actions exist, and in many contexts ecosystem-based adaptation will only be effective under the lowest levels of warming.

C3. Coastal communities face challenging choices in crafting context-specific and integrated responses to sea level rise that balance costs, benefits and trade-offs of available options and that can be adjusted over time (high confidence). All types of options, including protection, accommodation, ecosystem-based adaptation, coastal

advance and retreat, wherever possible, can play important roles in such integrated responses (high confidence).

Enabling Conditions

C4. Enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions coupled with coordinated sustained and increasingly ambitious adaptation actions (very high confidence). Key enablers for implementing effective responses to climate-related changes in the ocean and cryosphere include intensifying cooperation and coordination among governing authorities across spatial scales and planning horizons. Education and climate literacy, monitoring and forecasting, use of all available knowledge sources, sharing of data, information and knowledge, finance, addressing social vulnerability and equity, and institutional support are also essential. Such investments enable capacity-building, social learning, and participation in context-specific adaptation, as well as the negotiation of trade-offs and realisation of co-benefits in reducing short-term risks and building long-term resilience and sustainability. (high confidence) This report reflects the state of science for ocean and cryosphere for low levels of global warming (1.5°C), as also assessed in earlier IPCC and IPBES reports.

**National Academies of Science
Division on Earth and Life Sciences
Ocean Studies Board**

**Sustaining Ocean Observations to Understand Future Changes in Earth's Climate
(2017)**

<https://www.nap.edu/download/24919>

The goals of the study included considerations of what observations are most critical, the specifications for those observations, the present approaches to sustained ocean observing, and of the challenges to long-term ocean observing. A second stage of the study is scheduled to start later this month where new models or approaches to sustained ocean observing will be pursued.

What Are Ocean Observations for Climate?

- Ocean observations are made using both satellite and in situ (located within the water) instrumentation.
- In situ (in water) observations are carried out using fixed and mobile platforms such as tide gauges, data buoys, moorings, ship-based observations, profiling floats, ocean gliders, and surface drifters.
- Priority ocean variables observed for climate are sea state, ocean surface stress, sea ice, sea surface height, sea surface temperature, subsurface temperature, surface currents, subsurface currents, sea surface salinity, subsurface salinity, ocean surface heat flux, and dissolved inorganic carbon.
- The ocean observing enterprise is an end-to-end system built on engineering, operations, data management, information products, and the associated human capabilities, which are supported by the planning and governance by international coordination entities and by regional and national agencies.

Value of Sustained Observations

With the accumulation of greenhouse gases in the atmosphere, notably CO₂ from fossil fuel combustion, the Earth's climate is now changing more rapidly than at any time since the advent of human societies. Society will increasingly face complex decisions about how to mitigate the adverse impacts of climate change such as droughts, sea-level rise, ocean acidification, species loss, changes to growing seasons, and stronger and possibly more frequent storms. To make informed decisions, policy makers will need information that depends on understanding the dynamics of the planet's climate system. Because these dynamics will evolve as the climate warms, the ability to anticipate and predict future climate change will depend on ongoing observations of key climate parameters to tune and enhance models. Observations play

a foundational role in documenting the state and variability of components of the climate system and facilitating climate prediction and scenario development. Regular and consistent collection of ocean observations over decades to centuries would monitor the Earth's main reservoirs of heat, CO₂, and water and provides a critical record of long-term change and variability over multiple timescales. Sustained high-quality observations are also needed to test and improve climate models, which provide insights into the future climate system. With knowledge gained through these observations and models, more informed decisions can be made about how to respond and adapt to the impacts of climate change on national security, the economy, and society. Sustained observations of environmental variables are thus essential to advance understanding of the state of the climate system now and in the future.

Study Task and Approach

The committee was charged with considering processes for identifying priority ocean observations that will improve understanding of the Earth's climate processes, and the challenges associated with sustaining these observations over long time frames, and approaches for overcoming these challenges. The committee considered the priority variables that are most needed to address the ocean's role in climate while recognizing that there are important ocean variables to observe outside of the scope of the study.

Heat, Carbon, and Fresh Water Budgets

This report identifies three distinct global budgets that help define critical observations for understanding climate: heat, carbon, and fresh water. These were selected because of the central role the ocean plays in each and for their ability to inform climate model projections and detect changes within the climate system. Ocean observations have contributed to vital insights into changes in these budgets and informed understanding of other related ocean changes, such as sea-level rise. Uninterrupted time series of observations are required to distinguish natural variability of ocean processes from changing long-term climate trends. Although ocean general circulation models employ data assimilation methods to estimate the state of the ocean and provide quantitative estimates of how well the observations constrain these budgets, closing these budgets will require extension of ocean climate observations to the full depth of the ocean and into poorly sampled regions such as the polar seas. Additional research will be needed to develop the advanced observing capabilities needed to quantify the full suite of processes contributing to each budget.

Heat Budget

Ocean warming accounts for about 90 percent of the net global surface heat gain. Hence, accurate estimates of ocean heat content provide a fundamental index of the

present climate system that also will be a determinant of future global surface warming as ocean circulation returns heat stored in the depths to the sea surface. Because heat absorbed by surface ocean waters is transported laterally and vertically through the depth layers and basins of the ocean via mixing and currents, there is no single variable that can be measured to determine ocean warming.

Carbon Budget

About 30 percent of the CO₂ released by human activities has been absorbed by the ocean, reducing the amount in the atmosphere and the associated greenhouse effect. However, dissolved CO₂ becomes a weak acid that lowers the pH of sea water, a phenomenon termed ocean acidification, which will limit the capacity of the ocean to absorb more CO₂ in the future and can have negative effects on marine life.

Fresh Water Budget

The fresh water budget is important for understanding changes in the salinity of the ocean, a parameter that influences ocean circulation due to stratification, and therefore heat and carbon exchange between the ocean surface and the atmosphere.

Sea Level Reflects Heat and Budgets

Sea-level rise, one of the leading indicators of a warming climate, will have major impacts on coastal communities and economies, affecting shipping, national and homeland security, tourism, and other valuable societal activities. The ocean heat content provides estimates of rates of thermosteric sea-level rise, the rise in sea level caused by the expansion of the ocean as it absorbs increasing amounts of heat. The net fresh water input to the ocean, which increases when higher temperatures cause land ice to melt and run off into the ocean, is the other major contribution. To assess these components of the heat and fresh water budgets, in situ measurements of temperature and salinity are needed throughout the water column. Moreover, ocean current observations are required to evaluate the transport of heat and salt and their effects on regional sea level. Refining the calculations of these budgets based on a comprehensive set of in situ measurements will advance our understanding of global and regional sea-level change, which is essential for assessing risks to coastal communities and infrastructure in the United States, and to low-lying regions worldwide.

REPORT FINDINGS

Progress Achieved by Ocean Observations

Finding: The current ocean observing system has made significant contributions to better understanding the ocean's role in the Earth system, including its heat, carbon, and fresh water budgets, and to better understanding global and regional sea-level change. Sustaining, optimizing, and increasing ocean observing capability will further improve understanding of the ocean's role in climate.

Benefits of Ocean Observations Beyond Climate

Finding: The ocean observing system contributes not only to our understanding of climate variability and change, but also to a wide variety of other services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. This understanding of climate variability and change and other services underpins national defense, economic, and social policy decisions.

Observing System Operations

Finding: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses; all are essential elements for realizing the value of long-term, sustained observations.

The Global Ocean Observing System

Finding: The GOOS efforts are effective at promoting international cooperation to sustain the ocean climate observing system. Its guiding document, the Framework for Ocean Observing, and the associated procedures for establishing priority observation—the Essential Ocean Variables—are constructive for defining ongoing requirements (precision, frequency, spatial resolution) for sustained ocean observations and provide a solid foundation for selecting and prioritizing ocean variables for sustained observing.

Finding: Opportunities exist to increase the spatial coverage and multidisciplinary nature of sustained ocean observations through U.S./international (either bilateral or multilateral) coordination and sharing of resources.

Finding: Capacity building enhances international support for the sustained ocean observing system and is valuable for increasing international use of the information and sharing of observing responsibilities.

National Coordination, Planning, and Funding Challenge

Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

Finding: To avoid data gaps and ensure the required data quality and the accessibility of the data for monitoring climate over decades, ocean observing initiatives will need to plan for the end-to-end scope of expenses associated with observing programs, including appropriate logistical planning.

Finding: The absence of an overarching long-term (e.g., 10-year) national plan with associated resource commitments and lack of strong leadership presents a challenge for sustaining U.S. contributions to ocean observing, by inhibiting effective coordination and multiyear investments in the many components of the observing system.

New Technology Challenge

The limited investment in advancing technological capabilities is a challenge that, if addressed, will yield significant returns over the lifetime of sustained observing platforms through development of more robust and efficient sensors and platforms and through the maturation of observing methods to address existing and new scientific challenges.

Conclusion on Technology: Declining investments have slowed the development of new technology, which is proven to expand the capability, the efficiency, and therefore, the capacity of the observing system. If addressed, this investment will yield significant returns over the lifetime of sustained observing platforms through development of more robust and efficient sensors and platforms. Some philanthropic efforts have in part filled this gap and the OCP could encourage more support there.

Research Fleet Challenge

Research vessels are indispensable to the ocean observing system, providing direct observations and deployments of moored and drifting instruments. Ships require long-term planning and investment, and maintenance of a capable fleet of research vessels is an essential component of the U.S. effort to sustain ocean observing.

Conclusion on the Research Fleet: While new technology holds promise for access to the ocean, a capable fleet of research vessels, including those with global reach, is essential to sustaining the U.S. contribution to ocean observing.

Finding: The decreasing number of global- and ocean-class research vessels is creating a shortfall in the infrastructure required for sampling the global ocean and expanding collection into poorly sampled regions such as the polar seas.

The Challenge of Short-Term Funding

Finding: The continuity of ocean observations is essential for gaining an accurate understanding of the climate. Funding mechanisms that rely on annual budget approval or short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

Workforce Challenge

Finding: Direct scientific involvement in sustained observing programs, from design to implementation to analysis, synthesis, and publication, ensures that the ocean observing system will be robust in terms of data quality, incorporation of new methods and technologies, and scientific analyses; all are essential elements for realizing the value of long-term, sustained observations. The long-term investment required to develop and sustain the necessary expert workforce of the future is a challenge due to limited professional rewards or career incentives at research institutions and laboratories to ensure intergenerational succession of scientists, engineers, and technical staff.

Nonfederal Players

Finding: Raising awareness of the importance and value of sustained ocean climate observations could increase support for the observing system from multiple sectors, including philanthropic organizations.

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Murray's research interests are in marine geochemistry, with an emphasis on sedimentary chemical records of climate change, volcanism, and tropical oceanographic processes, and in the chemistry of the seafloor biosphere. A seagoing oceanographer, he has participated on many research cruises in various capacities around the globe. He has authored or co-authored nearly 100 peer-reviewed research papers, is a Fellow of the Geological Society of America, a former Trustee of SEA, and helped initiate and manage the Link Foundation's Ph.D. Fellowship Program in "Ocean Engineering and Instrumentation". Murray is a former Councilor of The Oceanography Society, and is currently on the Board of Directors of the American Geophysical Union. He was an elected Selectman in Scituate, MA, from 2006 to 2014, and has been active in town governance for many years.