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Federal Involvement in Ocean-Based Research and Development

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SUMMARY

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Multiple federal departments and agencies conduct ocean-based research, monitoring, and/or technological development. Federal departments and agencies also may support academic, commercial, and nonprofit ocean-based research activities. The interpretation of oceanographic data collected and studied by these federal departments and agencies provides information to domestic policymakers, including Members of Congress, on relevant societal issues. These issues may pertain directly to coastal communities, including U.S. island states and territories. Ocean-based issues related to climate change, environmental protection, and natural resource management also can extend beyond coastal communities.

The federal government generally is involved in ocean-based research, monitoring, and technological development to increase knowledge and understanding of the ocean. International interests also frame federal ocean work, as the ocean supports global trade and recreation. The federal departments and agencies involved in ocean-based research, monitoring, and technological development include the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management, the National Science Foundation (NSF), and the Office of Naval Research (ONR) of the Department of the Navy, among others.

Federal ocean data collection efforts are varied and make use of many different types of tools and technology. NOAA, ONR, and NSF own oceanographic research vessels that enable scientists to collect observational data with ship-based equipment (e.g., multibeam sonar sensors, sediment corers). Technology such as autonomous underwater vehicles, launched from land or ships, has the capability to collect and automatically send large volumes of data to nearby shore facilities or back to the vessel. In addition, remote- or human-operated vehicles and human technical divers can be used for exploration (including data collection and sampling) and visualization of the ocean. NASA, NOAA, and the USGS monitor ocean and coastal waters with satellites. Several federal departments and agencies also use deployed instruments (e.g., buoys, floats), stationary monitoring (e.g., tide gauges), and other approaches to collect oceanographic data and monitor the ocean. NSF funds extramural research, such as through grants for projects where nonfederal entities carry out various types of ocean-based research and analysis efforts.

Congress may be interested in the potential for federal ocean-based research to inform the nation's evolving understanding of the physical ocean. Some scientists and environmental and climate advocates argue that continuous, systematic ocean observations (e.g., temperature, salinity) may help identify climate impacts that contribute to ocean changes (e.g., warming, sea ice melt) and, in turn, may affect society. For example, NOAA maintains about half of the global fleet of Argo profiling floats, which drift with ocean currents, collecting oceanographic data. Stakeholders, and some Members of Congress, identified the Argo Program as one federal program that could benefit from improved float technology designed to expand the program's coverage to greater ocean depths.

The collection and study of bathymetric data (i.e., the depth of the seafloor relative to the surface of the ocean) and geological and geophysical surveys have provided scientists with the data necessary to better map and characterize the ocean environment. Mapping and characterization of ocean areas may provide both economic and environmental benefits that may be of interest to Congress. For example, knowledge of seafloor features and environments can be used to locate potential offshore oil and gas reserves and seabed minerals (e.g., critical minerals). At the same time, characterization of marine habitats can provide baselines for understanding whether and how vulnerable certain habitats might be to human disturbance (e.g., resource extraction activities) or climate change. Bathymetric data also can be used to identify geologic features that may produce marine geohazard events (e.g., earthquakes, tsunamis, marine landslides) to help safeguard coastal communities and marine infrastructure (e.g., pipelines, undersea cables). Conversely, ocean mapping and research can be costly and time consuming; some may question the relative priority of such activities compared with both other ocean-based efforts and other federal activities.

Contents

Figures

Tables

Appendixes

Contacts

Introduction

The Atlantic, Indian, Pacific, Arctic, and Southern Oceans (collectively, the *global ocean*) are interconnected and comprise about 71% of Earth's surface. The global ocean affects various U.S. economic sectors, including those in the *blue economy*,[1] and provides societal resources (e.g., coastal protection, storage of carbon). For example, the ocean influences Earth's weather in ways that can affect things such as the amount of snowpack and spring melt, the strength and intensity of hurricanes making landfall, and seasonal crop yields.

The ocean is also a major component of the global climate system, as it absorbs, retains, and transports heat, water, and carbon. Scientists estimate with high confidence that the global ocean has absorbed more than 90% of the atmosphere's human-induced excess heat; since the 1980s, it has very likely absorbed between 20% and 30% of total anthropogenic (human-related) carbon dioxide (CO_2) emissions.[2] Climate change impacts on the ocean (e.g., warming) have affected marine fisheries, the marine tourism and recreation sector, and global food security.[3] Many view the continued observation and monitoring of the global ocean as important tools for assessing climate change impacts on marine natural resources and related ecosystems.

Selected federal departments and agencies pursuing mission-based, long-term data collection and monitoring of the ocean include the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA); the National Aeronautics and Space Administration (NASA); the Department of the Interior's U.S. Geological Survey (USGS) and Bureau of Ocean Energy Management (BOEM); and the Department of the Navy's (DON's) Office of Naval Research (ONR). The National Science Foundation (NSF) is an independent agency that provides grant funding for short-term ocean research projects that investigate specific hypotheses and research questions. The NSF also supports research infrastructure (e.g., research facilities, oceanographic research vessels, equipment and instruments, and other resources). Oceanographic data collected and studied by these federal departments and agencies—and the academic, commercial, and nonprofit research the federal government helps support—provide information to domestic policymakers, including Members of Congress.

Congressional interest in federal ocean data collection and research is multifold and includes issues related to authorizing and funding specific ocean research activities and performing oversight on the implementation of federal ocean research. Congressional funding for federal departments and agencies that conduct ocean-based research allows for the continued monitoring of the ocean and the development of novel technologies to do so. In turn, Congress may use the data and knowledge gained by these federal departments and agencies to inform legislation and oversight. Ocean research may provide other benefits, such as supporting the blue economy and efforts to protect sensitive marine habitats and their wildlife. At the same time, the collection and monitoring of ocean data by the federal government can be time consuming and costly. Some

[1] Activities that may be considered part of the *blue economy* include living marine resources, coastal and marine construction, marine research and education, marine transportation and warehousing, marine professional and technical services, offshore minerals, coastal utilities, coastal and offshore tourism and recreation, nonrecreational ship and boat building, and national defense and public administration. For more information, see CRS In Focus IF12188, *What Is the Blue Economy?*, by Caitlin Keating-Bitonti and Eva Lipiec.

[2] Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *The Ocean and Cryosphere in a Changing Climate: A Special Report of the Intergovernmental Panel on Climate Change*, eds. Hans-Otto Pörtner et al., 2019, p. 9. Hereinafter referred to as IPCC, *Ocean and Cryosphere*.

[3] National Oceanic and Atmospheric Administration (NOAA), "Understanding Our Changing Climates," https://www.fisheries.noaa.gov/insight/understanding-our-changing-climate.

may question the relative priority of such efforts compared to both other ocean-based efforts and other federal activities.

This report provides an overview of the federal government's efforts to collect ocean-based data through observations and monitoring and to conduct and support federal and U.S-based extramural ocean-based scientific research. It also discusses selected federal grant making efforts for these purposes. The report further explores the how ocean-based data may illuminate the impacts of climate change (e.g., data collected through NOAA's Argo Program) and how interagency collaboration on the mapping and characterization of the seafloor and its environments may inform federal policy on deep-sea geohazards and natural resources.[4]

Federal Ocean Research Infrastructure and Equipment

Federal research infrastructure and equipment used to collect and monitor ocean data form the basis for much ocean research. The analysis of these data has the potential to elucidate threats (anthropogenic and natural) to the ocean and its changing nature, contribute to marine resource (e.g., offshore energy and seabed mineral) exploitation, help maximize commercial fisheries yields, and provide warnings for marine geohazard and storm events. The information gained from these analyses may inform federal policy that aims to protect the ocean, the economic sectors that depend on marine resources, and coastal communities.

Federal departments and agencies have established programs and projects that support ocean research, using federal and nonfederal assets for observations. These data are collected with various forms of equipment, such as satellites (NASA, NOAA, USGS); ships (NOAA, NSF, ONR, USGS); aircraft (NASA, NOAA); and various deployed objects, such as arrays, buoys, and floats (NOAA, NSF, USGS). In addition, federal agencies may use ocean data collected by international, regional, and private-sector partners and integrate these data into federal databases; for example, the European Organisation for the Exploitation of Meteorological Satellites' polar satellite system contributes to NOAA's Joint Polar System.[5] Stationary coastal equipment, such as tide and water-quality gauges (USGS), collect and monitor local oceanographic data. Ship-based equipment allows for detailed mapping (e.g., multibeam sonar sensors),[6] exploration (e.g., human technical divers), visualization (e.g., remote or human operated vehicles), and sampling (e.g., nets, tows, grab samplers, sediment corers) of targeted site locations. Autonomous underwater vehicles (AUVs), routinely launched from ships, collect and automatically send large volumes of data to a nearby shore facility or back to the vessel.

The below sections provide examples of individual federal department and agency ocean research efforts. The sections below do not provide an exhaustive list of all the departments and agencies and their respective programs that conduct ocean-based research.

[4] Marine geohazards include earthquakes, volcanic eruptions, landslides, and tsunamis.

[5] European Organisation for the Exploitation of Meteorological Satellites, "Metop Series," https://www.eumetsat.int/our-satellites/metop-series.

[6] A *multibeam sonar* sends out simultaneous sonar beams (sound waves) in a fan-shaped pattern to collect seafloor information surrounding the ship. For more information, see the Seafloor Bathymetry section in **Appendix A**.

National Oceanic and Atmospheric Administration

NOAA's mission includes improving the understanding of the natural world (ocean, climate, space, and weather), protecting those resources, and monitoring global weather and climate. To study the ocean, NOAA uses satellites, ships, remotely operated vehicles (ROVs), AUVs, aircraft, and other smaller deployed instruments (e.g., buoys). NOAA is structured in six line offices that cover various aspects of the natural world.[7] Four of NOAA's six line offices are applicable to this report. Those four line offices and their program offices are described below to illustrate some of the ocean research conducted by NOAA.

The National Environmental Satellite, Data and Information Service (NESDIS) manages the nation's operational environmental satellites and provides access to the environmental data they collect to support research and enhance national security and the economy.[8] Selected NOAA satellites (i.e., NOAA-20, Suomi National Polar-Orbiting Partnership, and Jason-3) are discussed in greater detail in the "National Aeronautics and Space Administration," below."[9]

The Office of Marine and Aviation Operations (OMAO) controls specialized aircraft and ships and oversees small boat and underwater activities (including human technical diving) that help achieve NOAA's environmental and scientific missions. It operates 15 ships, including the *Okeanos Explorer*, four manned aircraft, and several unmanned aircraft systems.[10]

The National Ocean Service (NOS) leads NOAA's navigation and charting activities and coordinates a federal interagency program dedicated to coastal and ocean observations and research. NOS's U.S. Integrated Ocean Observing System (IOOS) provides support, funding, guidance, and advice for tracking, predicting, managing, and adapting to environmental changes in the ocean, coastal system, and Great Lakes.[11] In addition to managing some federal ocean data and modeling systems, IOOS integrates certain nonfederal information into these systems. These systems can be used to inform decisionmaking on coastal monitoring, coastal and ocean development, and changes in the Arctic.[12]

The Office of Oceanic and Atmospheric Research (OAR) conducts various aspects of ocean research across at least four offices.

- The Office of Ocean Exploration and Research is the only federal organization dedicated to exploring the deep ocean.[13] NOAA's *Okeanos Explorer* is outfitted with the necessary technology to map the seafloor during research expeditions.[14] NOAA uses other infrastructure, such as aircraft equipped with remote sensing technology and submersible ROVs, to map the depth and shape of the seafloor.

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[7] NOAA, "NOAA Line Offices," https://www.corporateservices.noaa.gov/public/lineoffices.html.

[8] NOAA, "Our Mission," https://www.nesdis.noaa.gov/about/our-mission.

[9] NOAA, "Currently Flying," https://www.nesdis.noaa.gov/current-satellite-missions/currently-flying.

[10] NOAA, "Fleet," https://www.omao.noaa.gov/about.

[11] The Integrated Coastal and Ocean Observation System Act of 2009 (33 U.S.C. §§3601 et seq.) established the U.S. Integrated Ocean Observing System (IOOS). Prior to the passing of the 2009 act, no coordinated approach to coastal and ocean observing existed. NOAA, "IOOS by the Numbers," https://ioos.noaa.gov/about/ioos-by-the-numbers/.

[12] NOAA, "Societal Benefits," https://ioos.noaa.gov/about/societal-benefits/.

[13] NOAA, "About NOAA Ocean Exploration," https://oceanexplorer.noaa.gov/about/welcome.html.

[14] While the mission equipment onboard *Okeanos Explorer* is operated by NOAA's Office of Ocean Exploration and Research, the ship is managed by NOAA's Office of Marine and Aviation Operations. NOAA, "About NOAA Ship *Okeanos Explorer*," https://oceanexplorer.noaa.gov/okeanos/about.html.

This office also funds non-NOAA, U.S.-based researchers conducting ocean exploration to better document and understand the ocean.[15]

- The Climate Program Office manages a competitive grant program to fund high-priority climate science research on Earth's climate system, including its atmosphere, ocean, land, and ice. Research funded by these grants aims to quantify the amount of heat and CO_2 uptake by the global ocean, estimate rates of sea level rise, and provide adaptation tools for fisheries threatened by warming ocean waters, among other findings.
- The Ocean Acidification Program coordinates research and activities to better understand the ocean's chemistry, how it is changing, its rate of change, how change varies regionally, and how marine life (e.g., coral reefs), people, and the economy (e.g., the marine tourism and recreation sectors) are impacted by these changes. This program also provides funds for extramural research and ensures that data collected by funded projects are archived and accessible for future research use.[16]
- The objective of the Global Ocean Monitoring and Observing Program (GOMO), funded under OAR's Sustained Ocean Observing and Monitoring (SOOM) Program,[17] is to conduct continuous, in situ observations for ocean-based research, monitoring, and prediction. The GOMO supports the collection of more than 1 million oceanographic observations per day through various activities such as the Global Ocean Carbon Network and the Argo Program, among others.[18] The Global Ocean Carbon Network aims to help researchers better understand the ocean's role in the global carbon cycle, including how the ocean absorbs atmospheric CO_2 and distributes carbon throughout the global ocean. The Argo Program is composed of nearly 4,000 Argo Profiling Floats (**Figure 1**). These floats drift with currents across the global ocean, capturing over time a near-global record of ocean temperature, salinity, dissolved oxygen, and pH data.[19] The Argo Program is international, with participation and program funding from over 25 countries; NOAA maintains about half of the global fleet.[20]

[15] NOAA, "Federal Funding Opportunity," https://oceanexplorer.noaa.gov/about/funding-opps/welcome.html.

[16] NOAA, "Data Collection and Management," https://oceanacidification.noaa.gov/WhatWeDo/Data.aspx. For more information on ocean acidification, see CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec.

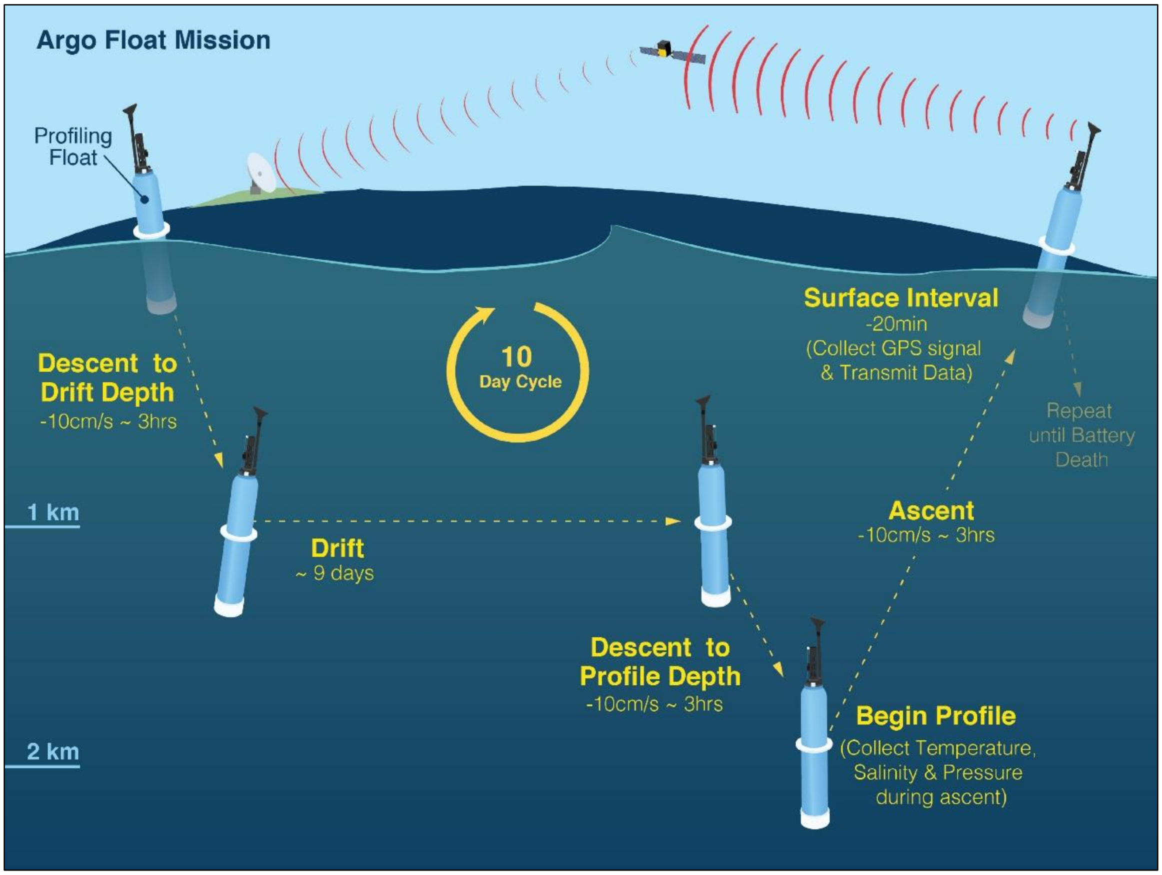
[17] NOAA's Sustained Ocean Observations and Monitoring (SOOM) Program, Project Activity (PPA) is a funding line in NOAA's budget. GOMO is the NOAA program that receives the initial allocation of the SOOM PPA; but SOOM is not GOMO's sole funding source. GOMO may use SOOM funds to support other programs that contribute to the overall priorities set by GOMO. Email correspondence with NOAA, Congressional Affairs Specialist, Office of Legislative and Intergovernmental Affairs, December 13, 2021.

[18] NOAA, "Global Ocean Monitoring and Observing," https://globalocean.noaa.gov/About-Us.

[19] NOAA, "NOAA Updates Sea Surface Temperature Dataset," https://www.ncei.noaa.gov/news/noaa-updates-sea-surface-temperature-dataset.

[20] NOAA, "Argo Program Achieves Milestone with Two Million Ocean Measurements," https://research.noaa.gov/article/ArtMID/587/ArticleID/2398.

Figure 1. NOAA Argo Profiling Float 10-Day Data Collection Cycle



Source: National Oceanic and Atmospheric Administration (NOAA), "The Argo Program," https://globalocean.noaa.gov/Research/Argo-Program.

Notes: km = kilometers; cm/s = centimeters per second; min = minutes; and hrs = hours. At the end of the 10-day cycle, Argo floats transmit data to satellites from which data are collected and processed for public use.

National Aeronautics and Space Administration

NASA studies the Earth, including its ocean and climate, the sun, and the solar system and beyond. In the 1960s, NASA began launching satellites to monitor Earth's weather. NASA has since expanded the types of Earth-observing data it collects with satellites designed to study Earth's climate system.

NASA's Earth Science Division plans, develops, and operates missions that support the science of Earth's atmosphere, land cover and vegetation, ocean currents and upper-ocean life, and continental and sea ice.[21] The bulleted list below is not an exhaustive list of all ocean research missions carried out by NASA but describes selected satellites that support NASA's Earth observing missions and supply ocean data to researchers.

- **Aqua.** This satellite's mission is to collect information about Earth's global water cycle, including sea surface temperature (SST) and ocean color. The satellite has four operating instruments that collect and transmit high-quality data to inform

[21] National Aeronautics and Space Administration (NASA), "NASA Earth Science Division Mission," October 18, 2021, https://svs.gsfc.nasa.gov/30065.

weather forecasts, carbon management, coastal management, disaster management, and water management.[22]

- **OCO-2.** This satellite is the first satellite to collect space-based measurements of atmospheric CO_2.[23] These measurements help identify areas that are natural CO_2 sinks, such as the ocean.
- **Terra.** This satellite is equipped with five instruments that are capable of comparing different aspects of Earth over time, including SST and ocean color.[24]
- **Jason-3.** This NASA and NOAA partnership satellite is equipped with technology to collect detailed sea level measurements (altimetry) to gain insight into ocean circulation and climate change.[25]
- **Sentinel-6.** This NASA and NOAA partnership satellite is equipped with technology capable of collecting sea level measurements within 1 centimeter of precision.[26]
- **GRACE-FO.** This satellite broadly tracks Earth's water, including ice sheets and glaciers, and sea level changes due water additions to the ocean.[27]
- **ICESat-2.** This satellite measures Earth's ice coverage within 4 millimeters of precision using its only onboard instrument, the Advanced Topographic Laser Altimeter System.[28]
- **Landsat 8 and 9**. These satellites are part of a collaboration between NASA and USGS and primarily collect data on Earth's land surface, but also provide information on shallow coastal seafloor *bathymetry* (i.e., the depth of the seafloor relative to the surface of the ocean).[29]
- **Suomi National Polar-Orbiting Partnership (NPP).** This satellite was developed by NASA for NOAA's Joint Polar Satellite System to provide data for weather forecasts and extreme storm events. Suomi NPP carries five research instruments to monitor the climate system (e.g., ocean color) while collecting the operational requirements for weather forecasting (e.g., SST), demonstrating the multifunctional nature of satellite technology.[30]
- **NOAA-20.** This satellite, Suomi NPP's successor and also built by NASA for NOAA's Joint Polar Satellite System, collects data on SST and ocean color.[31]

[22] NASA, "Aqua Earth-Observing Satellite Mission," https://aqua.nasa.gov/.

[23] NASA, "Quick Facts," https://ocov2.jpl.nasa.gov/mission/quick-facts/.

[24] NASA, "Terra Instruments," https://terra.nasa.gov/about/terra-instruments.

[25] NASA, "Jason-3," https://www.jpl.nasa.gov/missions/jason-3.

[26] NASA, "Sentinel-6 Mission Overview," https://www.nasa.gov/sentinel-6/overview.

[27] NASA, "Mission," https://gracefo.jpl.nasa.gov/mission/overview/.

[28] Anna Heiney, "ICESat-2 Successfully Launched on Final Flight of Delta II Rocket," NASA ICESat-2 blog, September 15, 2018, https://blogs.nasa.gov/icesat2/.

[29] NASA, "Landsat 8 Mission Details," https://landsat.gsfc.nasa.gov/satellites/landsat-8/landsat-8-mission-details/. For more information, see CRS Report R46560, *Landsat 9 and the Future of the Sustainable Land Imaging Program*, by Anna E. Normand.

[30] NASA, "NPP Mission Overview," https://www.nasa.gov/mission_pages/NPP/mission_overview/index.html. For more information on NOAA's polar-orbiting weather satellites, see CRS Report R44335, *Minding the Data Gap: NOAA's Polar-Orbiting Weather Satellites and Strategies for Data Continuity*, by Peter Folger.

[31] NOAA, "Joint Polar Satellite System (JPSS) Program Office," https://www.jpss.noaa.gov/.

U.S. Geological Survey

The USGS is a scientific agency within the Department of the Interior (DOI).[32] USGS scientists monitor, analyze, and predict the current and evolving dynamics of the Earth. A core USGS mission is mapping, which includes coastal maps generated from bathymetric surveys;[33] generally, NOAA is the primary federal source for ocean bathymetric data. The USGS also collects, monitors, and analyzes natural resources data, including for resources found in the ocean, such as sand and gravel for construction and critical minerals required for renewable technologies.[34]

At least three USGS programs are engaged in ocean-based research.

- The Coastal/Marine Hazards and Resources Program, within the Natural Hazards Mission Area, collects and manages data, such as information about gas hydrates, hydrothermal vent deposits, and rare Earth minerals.[35] This program also supports other ocean science topics, such as mapping the extent of the continental shelf, studying factors related to sea level rise, and conducting research on ocean ecosystems, including benthic ecosystems (i.e., organisms living on or in seafloor sediments).
- The Groundwater and Streamflow Information Program, within the Water Resources Mission, deploys, operates, and retrieves sensors for coastal storm events, including tide gauges and other water sensors (see **Table 1** and **Table 2**). The Coastal/Marine Hazards and Resources Program augments data collection and other activities associated with storm events conducted by the Groundwater and Streamflow Information Program as needed.[36]
- The Climate Research and Development Program, within the Ecosystems Mission Area, supports monitoring of the Arctic, sea ice, and sea level rise.[37] This program also collects and analyzes deep-sea sediments to reconstruct changes in past climate and oceanographic conditions.[38]

Bureau of Ocean Energy Management

BOEM, an agency within DOI, manages the development of the nation's energy and mineral resources on the outer continental shelf (OCS), which includes submerged lands, subsoil, and

[32] For more background on the USGS, see CRS In Focus IF12097, *The U.S. Geological Survey (USGS): Background and FY2023 Appropriations*, by Anna E. Normand.

[33] U.S. Geological Survey (USGS), "Sea Floor Mapping Group," https://www.usgs.gov/centers/whcmsc/science/sea-floor-mapping-group.

[34] USGS, "Ocean Resources," https://www.usgs.gov/centers/whcmsc/science/ocean-resources; USGS, "Celebrate June as Oceans Month," June 2, 2016, https://www.usgs.gov/news/featured-story/celebrate-june-oceans-month.

[35] USGS, "Coastal and Marine Hazards and Resources Program," https://www.usgs.gov/natural-hazards/coastal-marine-hazards-and-resources/science/ocean-resources.

[36] USGS funding for these activities primarily comes from reimbursable partners (typically the Federal Emergency Management Agency, FEMA) as storm events occur. Email correspondence with USGS, Congressional Liaison, Congressional Liaison Office, on January 7, 2022.

[37] USGS, "Science," https://www.usgs.gov/programs/climate-research-and-development-program/science.

[38] USGS, "Paleoclimate Research," https://www.usgs.gov/programs/climate-research-and-development-program/science/paleoclimate-research.

seabeds under U.S. jurisdiction.[39] BOEM conducts geological and geophysical (G&G) surveys to obtain data on oil and gas reserves located on the OCS, identify sites for offshore renewable energy structures, and locate seabed mineral resources.[40]

BOEM conducts two types of G&G surveys: deep penetration airgun surveys and high-resolution geophysical (HRG) surveys to characterize the subsurface of the seafloor (i.e., different layers of rock beneath the seafloor).[41] Deep penetration airgun surveys are also used for oil and gas exploration. HRG surveys can be used for oil and gas exploration, siting for renewable energy structures, and sand and gravel identification. HRG equipment can include multibeam sonars, sidescan sonars, and sub-bottom profilers. These surveys typically operate at higher frequencies and image smaller structures at higher levels of detail as compared with airgun surveys.

BOEM has four programs, among other activities, that involve ocean-based studies and the management of related scientific research and data.

- The Conventional Energy Program, among other activities, conducts assessments of the oil and gas resource potential on the OCS, including G&G surveys to obtain data useful for oil and gas exploration, inventories of oil and gas reserves, and economic evaluations.
- The Renewable Energy Program, among other activities, funds and manages scientific research related to renewable energy projects on the OCS (e.g., potential environmental and ecological stressors during the construction and operation of offshore renewable energy facilities).
- The Environmental Program funds and manages environmental studies, including, but not limited to, studies of physical oceanography, protected species, economics, and cultural resources.
- The Marine Minerals Program, among other activities, conducts environmental studies and assessments, performs resource evaluation studies, and contributes data for bathymetric maps. Initiatives include the National Offshore Critical Mineral Inventory, the National Offshore Sand Inventory, and the Marine Minerals Information System (with information on OCS sand and gravel resources).

National Science Foundation

NSF promotes the progress of science by funding extramural research, largely through grants awarded in support of academic research.[42] The types of data collected, and the modes of data collection and observation, depend on the awarded research project. Funding duration for NSF

[39] The Outer Continental Shelf Lands Act of 1953 (OCSLA, 43 U.S.C. §§1331-1356b) defines the outer continental shelf (OCS) as all federally controlled submerged lands, subsoil, and seabed. The OCS generally begins 3 nautical miles (international nautical mile = 6,076.1 feet) off the coastline and extends for at least 200 nautical miles to the edge of the exclusive economic zone, or farther if the continental shelf extends beyond 200 nautical miles. For more information, see CRS Report RL33404, *Offshore Oil and Gas Development: Legal Framework*, by Adam Vann.

[40] Bureau of Ocean Energy Management (BOEM), "Fact Sheet: Geological and Geophysical (G&G) Surveys," https://www.boem.gov/sites/default/files/about-boem/BOEM-Regions/Atlantic-Region/GandG-Overview.pdf.

[41] Ibid.

[42] For more information on the National Science Foundation (NSF), see CRS Report R46753, *The National Science Foundation: An Overview*, by Laurie A. Harris.

grants generally ranges from one to five years, with an average of three years for research grants.[43]

The Division of Ocean Sciences (OCE), within the NSF Directorate for Geosciences, provides funding support to advance understanding of all aspects of the global ocean (including human interactions),[44] including through competitive grants. Other NSF Directorates (e.g., Directorate for Biological Sciences, Directorate for Mathematical and Physical Sciences) also may support aspects of ocean research. In general, about 30% of OCE's funding each year goes to new research grants, with the remaining 70% of funds supporting grants made in previous years and research infrastructure.[45] Also within NSF's Directorate for Geosciences is the Office of Polar Programs (OPP), which provides research funding for scientists supported by NSF and by other federal departments and agencies studying the polar regions, including the Southern and Arctic Oceans. OPP leverages both interagency and international partnerships.

Both OCE and OPP support the U.S. Global Change Research Program (USGCRP),[46] which includes infrastructure programs that focus on observing today's changing ocean and better understanding past climate events to inform modeling of future climate change. One of the two goals USGCRP set for FY2023 is to advance scientific knowledge of the integrated natural and human components of the Earth system, which includes the role of the ocean in climate change.[47]

NSF is part of the University-National Oceanographic Laboratory System (UNOLS),[48] which provides a forum for the research and education community and the federal government to work cooperatively on oceanographic research while coordinating a federally supported Academic Research Fleet (ARF).[49] For example, the R/V *Sikuliaq* is a research vessel owned by the NSF and operated by the College of Fisheries and Ocean Sciences at the University of Alaska Fairbanks that specializes in polar-focused ocean research. OCE also oversees the Regional Class Research Vessel (RCRV) project, which is currently funding the construction of three ships for inclusion in the ARF to support the needs of researchers in coastal zones.[50] The first of these three new ships is planned for delivery in 2023, with subsequent vessels being delivered 6 and 12 months thereafter.[51]

NSF also provides support to the International Ocean Discovery Program (IODP), an international marine research collaboration that uses research platforms to drill and recover seafloor sediments that can be used to study the dynamics of the sub-seafloor and the past 200

[43] NSF, *Merit Review Process: Fiscal Year 2019 Digest*, December 2020, pp. 7 and 20.

[44] NSF, "About the Division of Ocean Sciences (OCE)," https://www.nsf.gov/geo/oce/about.jsp.

[45] NSF, "FY 2022 NSF Budget Response to Congress—Geosciences," p. GEO-11, https://www.nsf.gov/about/budget/fy2022/pdf/49_fy2022.pdf.

[46] The U.S. Global Change Research Program (USGCRP) was mandated by Congress in the Global Change Research Act of 1990 (P.L. 101-606) to coordinate federal research and investments across 13 departments and agencies to advance understanding of the changing Earth system.

[47] NSF, *National Science Foundation FY2023 Budget Response to Congress*, pp. Climate-9 and GEO-1, https://www.nsf.gov/about/budget/fy2023/pdf/fy2023budget.pdf. Hereinafter referred to as "FY2023 NSF Budget Response."

[48] University-National Oceanographic Laboratory System (UNOLS), "UNOLS Charter," https://www.unols.org/sites/default/files/UNOLS_Charter_2019.pdf.

[49] Academic Research Fleet vessels support the needs of all federal oceanographic research stakeholders, particularly NSF, NOAA, and ONR. FY2023 NSF Budget Response, p. Research Infrastructure-54.

[50] The National Academies of Sciences, Engineering, and Medicine, *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* (Washington, DC: The National Academies Press, 2015), p. 3.

[51] FY2023 NSF Budget Response, p. Overview-12.

million years of Earth's history.[52] Seafloor sediments can be used to reconstruct the extent of sea ice during past glaciation events. The sediments also reflect past changes in deep-sea circulation patterns, which help distribute and sequester (or bury) atmospheric CO_2 in the ocean.

U.S. Department of the Navy

DON produces meteorological and oceanographic knowledge to advance the U.S. military mission and to provide secondary benefits to the United States. ONR within the DON aims to provide science- and technology-based solutions for current and future naval challenges. ONR oversees the execution of the science and technology (S&T) portion of DON's overall research and development account. ONR addresses a wide range of potential S&T issues of interest to the Navy. A portion of those issues are ocean-based, including ocean engineering, maritime sensing, undersea and remote sensing system development, ocean acoustics, Arctic changes, and physical oceanography monitoring.

ONR and NSF are the two primary federal support agencies of the UNOLS fleet of academic research vessels. ONR owns six UNOLS academic research vessels and, together with the operating institutions, coordinates their research missions and ship schedules.[53]

DON's Naval Oceanographic Office (NAVOCEANO) collects and analyzes oceanographic data to support national security and provide knowledge of the maritime battlespace. Civilian and military members of NAVOCEANO are generally qualified as hydrographers and survey technicians capable of hydrographic surveys (descriptions of seafloor features) anywhere in the world.[54]

Oceanographic Data

Oceanographic data consist of measurements of the physical state of the ocean (e.g., sea level is a physical variable) and the amount of chemical elements in the seawater (e.g., dissolved oxygen is a biogeochemical variable). Oceanographic data provide a basis for insights into the ocean ecosystem and its changing environment, aspects of climate change, and the geographic distribution and availability of marine resources. Physical oceanographic data (**Table 1**) also can provide information on oceanographic processes, such as ocean upwelling (**Figure 2**) and ocean current and circulation patterns. Whereas a single oceanographic variable can provide insight into various characteristics of the ocean, the combination of more than one physical or biogeochemical variable often can provide additional confidence about the scientific interpretations of the ocean's current and future state through scientific modeling studies.

Physical oceanographic variables are collected through an array of instrumentation and used for various purposes. Selected common physical oceanographic data are summarized below in **Table 1**. These data are discussed in more detail in **Appendix A**.

[52] Jason Daley, "This 340-Million-Year-Old Ocean Crust Could Date Back to Pangaea," *Smithsonian Magazine*, August 17, 2016, https://www.smithsonianmag.com/smart-news/oldest-bit-seafloor-discovered-mediterranean-180960153/.

[53] UNOLS "UNOLS Designated Vessels," https://www.unols.org/ships-facilities/unols-vessels/unols-designated-vessels/unols-designated-vessels.

[54] Naval Meteorology and Oceanography Command, "Fleet Survey Team (FST)," https://www.cnmoc.usff.navy.mil/Our-Commands/Naval-Oceanographic-Office/Fleet-Survey-Team/.

Table 1. Selected Physical Oceanographic Variables

(common physical oceanographic data collected and studied by federal departments and agencies)

Physical Oceanographic Variable	Instrumentation and Equipment Examples	Selected Uses/Purposes
Ocean Temperature	Argo Profiling Floats (NOAA); Unmanned Surface Wave Gliders (NOAA);[a] CTD Sensors (NOAA/USGS);[b] Research Vessels (NOAA); Submersible ROVs (NOAA); Earth-Observing Satellites (NOAA/NASA); Water-Quality Gauge (USGS)	• Forecast and track pending short- and mid-term weather events (including storms and hurricanes) and long-term climate patterns, such as the El Niño Southern Oscillation • Track ocean circulation patterns, such as the Gulf Stream • Monitor ocean upwelling, which can be applied to track the occurrence of specific marine species
Ice Elevation and Thickness	Earth-Observing Satellites (NOAA/NASA); Research Vessels (NSF); Moored (Stationary) Buoys (NOAA); Aircraft (NASA)	• Understand impact of climate change on polar regions • Predict and quantify rate of sea level rise • Predict freshening (salinity decline) of surface ocean water in polar regions
Sea Level	Earth-Observing Satellites (NOAA/NASA); Tide Gauges (NOAA/USGS); Water-Level Sensors (USGS)	• Predict coastal sea level trends and flooding • Quantify the rate of sea level rise • Inform safe vessel navigation
Chlorophyll (ocean color)	Earth-Observing Satellites (NOAA/NASA)	• Monitor ocean upwelling and provide an estimate for living phytoplankton in the near-surface water
Seafloor Bathymetry	Research Vessels Equipped with Geological and Geophysical Survey Equipment (NOAA/BOEM/USGS); Submersible ROVs (NOAA); Aircraft Equipped with lidar (NOAA); Earth-Observing Satellites (NASA/USGS)	• Quantify water depth • Provide information on seafloor sediment type that could aid siting of natural resources • Identify seafloor geologic features (faults or subduction zones) that could produce natural hazards (earthquakes or tsunamis) • Determine the extent of the U.S. continental shelf[c] • Inform safe vessel navigation

Source: Information for this table is derived from NASA, NOAA, NSF, and USGS websites. For additional information and source data, refer to **Appendix A**.

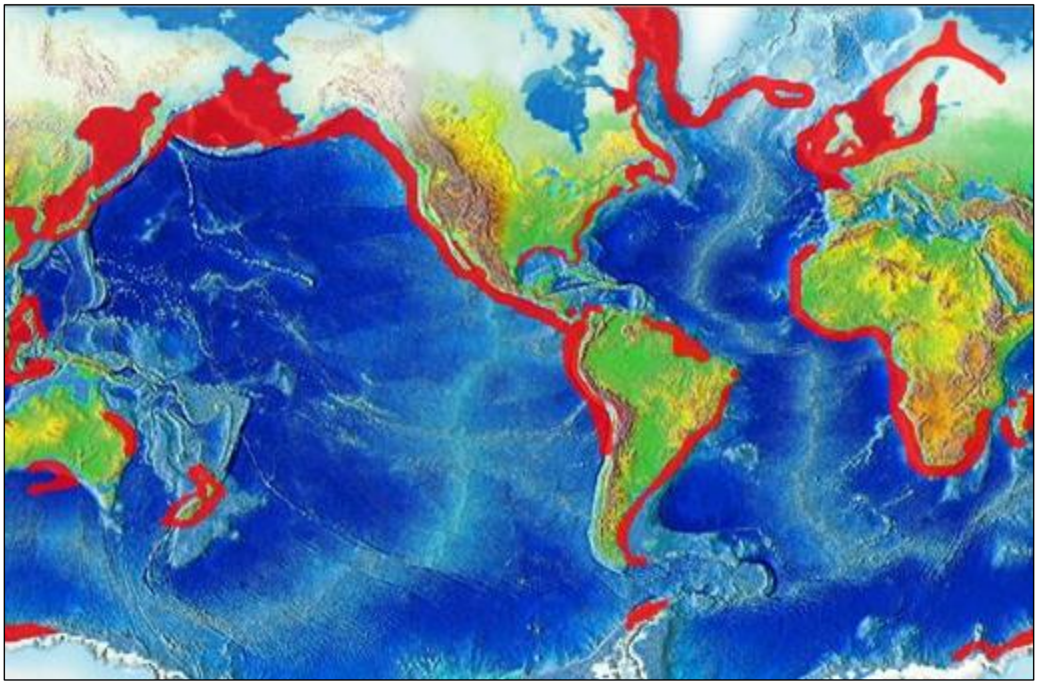
Notes: BOEM = Bureau of Ocean Energy Management; CTD Sensors = Conductivity, Temperature, and Depth Sensors; lidar = light detection and ranging; NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration; National Science Foundation = NSF; ONR = Office of Naval Research; ROV = remote-operated vehicle; USGS = U.S. Geological Survey.

a. Wave gliders are inexpensive surfboard-looking autonomous vehicles that collect surface ocean data.

b. A CDT sensor detects how the conductivity and temperature of the seawater changes with water depth, which can be used to derive salinity.

c. For more information, see CRS Report R41153, *Changes in the Arctic: Background and Issues for Congress*, coordinated by Ronald O'Rourke.

Figure 2. Major Areas of Coastal Upwelling



Source: National Oceanic and Atmospheric Administration (NOAA), "Upwelling," https://oceanservice.noaa.gov/education/tutorial_currents/03coastal4.html.

Notes: Areas of major coastal upwelling are shown in red. Ocean upwelling occurs when wind energy pushes sea surface water in a specific direction, allowing deep water to move to the surface. Upwelled waters are rich in nutrients, and ocean upwelling is a natural fertilization process for the surface ocean, stimulating the base of the marine food web. For additional information on ocean upwelling, see text box entitled "Ocean Upwelling" in **Appendix A**.

The concentrations of biogeochemical variables (**Table 2**) in seawater are influenced by mixing of waters with different concentrations (e.g., upwelled deep-sea water mixing with near-surface water), biogeochemical processes (e.g., the marine carbon cycle), and atmospheric inputs (e.g., diffusion of dissolved oxygen across the atmosphere-surface water interface), among other factors. Anthropogenic CO_2 emissions and agricultural or wastewater discharge have also altered biogeochemical variables (e.g., pH and dissolved oxygen).[55] Selected common biogeochemical oceanographic data are summarized below in **Table 2**. These data are discussed in more detail in **Appendix B**.

[55] For information on the effects of human-associated discharge on coastal ocean waters, see CRS Report R46921, *Marine Harmful Algal Blooms (HABs): Background, Statutory Authorities, and Issues for Congress*, by Eva Lipiec.

Table 2. Selected Biogeochemical Oceanographic Variables

(common biogeochemical oceanographic data collected and studied by federal departments and agencies)

Biogeochemical Oceanographic Variable	Instrumentation and Equipment Examples	Selected Use/Purpose
Salinity	Argo Profiling Floats (NOAA); Unmanned Wave Gliders (NOAA); Submersible ROVs (NOAA); CTD Sensors (NOAA/USGS); Water-Quality Gauge (USGS)	• Provide insight into the water cycle • Trace ocean circulation patterns • Monitor runoff from land or ice melt • Predict hurricane intensity
Dissolved Oxygen	Argo Profiling Floats (NOAA); Unmanned Wave Gliders (NOAA); Submersible ROVs (NOAA); Water-Quality Gauge (USGS)	• Serve as indicator of the health of the marine ecosystem • Correlate with surface ocean temperature
pH	Argo Profiling Floats (NOAA); Unmanned Wave Gliders (NOAA); Moored Buoys Equipped with CO_2 Sensors (NOAA); Earth-Observing Satellites (NASA/NOAA);	• Quantify rate of anthropogenic carbon uptake by the ocean • Serve as indicator for ocean acidification

Source: Information for this table is derived from NASA, NOAA, and USGS websites. For additional background information and source data refer to **Appendix B**.

Notes: CO_2 = carbon dioxide; CTD Sensors = Conductivity, Temperature, and Depth Sensors; NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration; USGS = U.S. Geological Survey. A CDT sensor detects how the conductivity and temperature of the seawater changes with water depth, which can be used to derive salinity.

Ocean Data Trends and Climate Change

Ocean data and observation trends over time have informed scientific reports that have highlighted the nature and rate of change in the global ocean, as well as the potential impacts of these changes.

- **Ocean Temperature.** Warming surface ocean waters affect weather patterns and storms, including hurricanes. The 2019 Intergovernmental Panel on Climate Change (IPCC) *Special Report on the Ocean and Cryosphere in a Changing Climate* found evidence for an increase in the global proportion of category 4-5 tropical cyclones in recent decades; the proportion of high intensity tropical cyclones is projected to increase with continued warming.[56]
- **Ice.** Warming near-surface air temperatures in the Arctic are melting continental ice (ice sheet and glacier) across the region, including the Greenland Ice Sheet, and contributing to sea ice melt on the Arctic Ocean.[57] The climate modeling results for the mid- and high-greenhouse gas emissions scenarios published in the 2021 IPCC *Sixth Assessment Report* project the Arctic to be "practically" sea-ice free during the month of September between 2050-2100.[58]

[56] "Summary for Policymakers," in IPCC, *Ocean and Cryosphere*, p. 11. NOAA, "Global Warming and Hurricanes," April 11, 2023, https://www.gfdl.noaa.gov/global-warming-and-hurricanes/.

[57] T. J. Ballinger et al., "Surface Air Temperature," in NOAA, *2022 Arctic Report Card*, December 2020, p. 2.

[58] IPCC, "Summary for Policymakers," in *Changing Climate 2021: The Physical Science Basis*, eds. V. Masson-Delmotte et al., 2021, pp. SMP-29–SMP-30. Hereinafter referred to as IPCC, *AR6 Physical Science Basis.*

- **Sea level.** Continental ice melt and thermal expansion of ocean water are contributing to rising sea levels.[59] From 2006 to 2018, continental ice melt was the dominant contributor to global sea level rise.[60] Continuous data on variations in sea level inform scientists on the rate of sea level rise and the regions most susceptible to coastal flooding. The average global sea level rise from 2006 to 2018 was 3.7 millimeters per year.[61]
- **Dissolved Oxygen.** Declining oxygen levels in seawater correlate with warming ocean waters. Warmer water holds less dissolved gases (e.g., oxygen) than colder water. Trends published in the physical science report of the 2021 IPCC *Sixth Assessment Report* showed a decline in surface dissolved oxygen levels (deoxygenation) in all ocean basins. The IPCC attributed this decline, with medium confidence, to surface ocean warming.[62]
- **pH.** Declining seawater pH levels are attributed to the global ocean's increased absorption of anthropogenic atmospheric CO_2. Since the beginning of the Industrial Revolution, the pH of global surface ocean has decreased by 0.1 pH units (from an average pH of 8.2 to 8.1), equivalent to a 25%-30% increase in ocean acidity.[63]

Selected Issues for Congress

Research and analysis of ocean processes, resources, and potential future changes to these processes and resources have the potential to inform congressional deliberations regarding ocean policy and ocean management. Congress also may be interested in these efforts for their potential to support public- and private-sector economic activities that rely on the ocean or facilitate the protection of sensitive habitats and their wildlife.

A potential issue facing Congress is to what extent, if any, to continue supporting and directing federal ocean science research and development and, if so, which efforts to prioritize and how to guide departments and agencies in this work. Scientific knowledge of the ocean evolves as new information and exploration technology becomes available. Thus, some scientists and environmental and climate advocates have called for continuous, systematic ocean research observations and monitoring by federal government, as well as funding for new endeavors. Supporters of these efforts emphasize the modern challenges of ocean management and the opportunities the ocean presents to address environmental and societal issues. In addition, some supporters see this research as contributing to the U.S. global leadership role in ocean science. At the same time, funding for ocean research can be costly; thus, some may question the relative priority of some work, compared to both other ocean-based efforts and other federal activities.

[59] Because water expands as it warms (thermal expansion), warming ocean water will cause sea level rise.

[60] "Summary for Policymakers," in IPCC, *AR6 Physical Science Basis*, p. SMP-14.

[61] Ibid, p. SMP-6.

[62] Ibid.

[63] For more information on the effects of anthropogenic CO_2 emissions on seawater pH, see CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec. NOAA, "Ocean Acidification," https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification; Environmental Protection Agency (EPA), "Understanding the Science of Ocean and Coastal Acidification," https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification.

Ocean Data and Research Needs Related to Climate Change

Some scientists and environmental advocates view the ocean as having a key role in mitigating climate change,[64] and they view federal spending in ocean monitoring and observational technologies as one means to better understand the ocean-climate nexus. Congress may consider whether the current investment is sufficient to provide adequate information on the potential impacts of climate change on the global ocean and its resources and, conversely, on the ways in which ocean processes influence global climate.[65]

Some believe increasing investments in certain ocean programs would allow ocean-based research to capitalize on technology advancements.[66] For example, the Argo Program, established in 1998, could be advanced through developing and deploying a fleet of floats that extend the typical profiling depth of 2,000 meters to 6,000 meters (Deep Argo) and a fleet that includes additional biogeochemical sensors to study carbon and nutrient cycling in the ocean (Biogeochemical Argo).[67] Congress funds NOAA's Sustained Ocean Observing and Monitoring Program (SOOM), projects, and activities on a year-to-year basis, from which NOAA determines and allocates the amount of funds to the Argo Program (**Table 3**). Funding support for the Argo Program has remained relatively constant since 2004 (with variations), with funding priority directed to sustaining the current fleet of Argo floats.[68] Some Members of Congress have proposed increases for Argo funding; for example, in FY2022, Congress directed NOAA to expand coverage of the Biogeochemical Argo fleet.[69]

[64] The global ocean absorbs CO_2 emissions from human activities (i.e., the combustion of fossil fuels), helping to offset the buildup of anthropogenic CO_2 in the atmosphere.

[65] The 117th Congress provided funding to NOAA to advance ocean and climate research. P.L. 117-169, a budget reconciliation measure commonly referred to as the Inflation Reduction Act of 2022 (IRA), appropriated $150 million in FY2022 (available through FY2026) to NOAA, with the goal of accelerating advances and improvements in research of atmospheric and ocean processes that relate to climate and weather, among others. In addition, Section 40004 of the IRA appropriated $50 million in FY2022 (available through FY2026) to NOAA for climate research competitive grants relating to ocean and other processes and associated impacts to marine species and coastal habitat.

[66] For example, Dean Roemmich et al., "On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array," *Frontiers in Marine Science*, vol. 6 (August 2019), p. 2.

[67] Successful prototype float deployments of Deep Argo floats took place in 2013-2015. These prototypes were able to reach approximately 6,000 meters below sea level. Testing of Biogeochemical Argo floats equipped with sensors for dissolved oxygen, nitrate, pH, chlorophyll fluorescence, and particulate backscatter began in 2012. Scripps Institution of Oceanography Argo Program Office, "Frequently Asked Questions," https://argo.ucsd.edu/faq/#who; NOAA Research News, "NOAA Invests in New Tools to Measure the Ocean," https://research.noaa.gov/article/ArtMID/587/ArticleID/2561.

[68] Scripps Institution of Oceanography Argo Program Office, *U.S. Argo National Report to Argo Steering Team-22*, March 2021, https://argo.ucsd.edu/wp-content/uploads/sites/361/2021/03/USA_national_report_AST22v1.pdf.

[69] H.Rept. 117-97 referenced by the explanatory statement accompanying the FY2022 Consolidated Appropriations Act (P.L. 117-103).

Table 3. Congressional Appropriations Applied to NOAA Argo Program

Program	FY2020 Enacted Appropriations	FY2021 Enacted Appropriations	FY2022 Enacted Appropriations	Description
Argo Program	$11,491,000	$11,495,000	$12,100,000	Amount directed toward Argo Program from total SOOM appropriations[a]
Other Argo Initiatives	$3,600,000	$3,780,000	$3,000,000	Amount appropriated to other programs, projects, and activities that was used for Deep Argo and Biogeochemical Argo
IIJA Funding for the Argo Program			$850,000	Amount appropriated through SOOM programs, projects, and activities
Total Argo Funding	**$15,091,000**	**$15,275,000**	**$15,950,000**	—

Source: Email correspondence with NOAA, Congressional Affairs Specialist, Office of Legislative and Intergovernmental Affairs, November 18, 2021 and March 29, 2023.

Notes: NOAA = National Oceanic and Atmospheric Administration; IIJA = Infrastructure Investments and Jobs Act of 2021 (P.L. 117-58); SOOM = Sustained Ocean Observing and Monitoring Program.

a. SOOM enacted appropriations were $45,000,000 in FY2020, $45,408,000 in FY2021, and $49,000,000 in FY2022.

Applications of Ocean Exploration and Bathymetric Data

Congress has shown, and continues to show, interest in mapping the ocean to inform ocean policies related to marine geologic hazards, environmental protections, and seabed mineral resource deposits, among other policy considerations. According to reports, 50% of the U.S. coastal, ocean, and Great Lakes waters remain unmapped; a fraction of the mapped areas have been explored or characterized.[70] Technological advances and the collection and study of modern bathymetric data have allowed for greater and more detailed mapping, exploration, and characterization of the ocean environment.[71] Congress may consider how federal efforts to map, explore, and characterize the U.S. ocean and coastal waters can complement other ocean-related policies and whether to direct federal agencies to prioritize certain U.S. ocean and coastal waters for mapping activities.

Congress also may wish to consider providing oversight on how federal agencies prioritize U.S. ocean and coastal mapping activities. The Ocean and Coastal Mapping Integration Act of 2009 (P.L. 111-11) authorized appropriations intended to facilitate federal mapping activities of U.S.

[70] NOAA, "Progress Report: Unmapped U.S. Waters," https://iocm.noaa.gov/documents/mapping-progress-report2023.pdf.

[71] Modern bathymetric data are data collected post 1960. NOAA, "U.S. Bathymetric Coverage and Gap Analysis," https://iocm.noaa.gov/seabed-2030-bathymetry.html.

ocean and coastal waters and the Great Lakes.[72] In 2021, Congress provided specific direction for NOAA to use $2 million of its appropriated funds to support mapping, exploration, and characterization strategies, such as the National Strategy for Mapping, Exploring, and Characterizing of the United States Exclusive Economic Zone (hereinafter referred to as the NOMEC Strategy)[73] and the Alaska Coastal Mapping Strategy (ACMS).[74] The majority of the $2 million was used for collaborative mapping data acquisition in Alaska in support of ACMS.[75] Congress may wish to review how NOAA has used these funds or provide additional direction on where funds should be applied to specific U.S. ocean and coastal areas for mapping activities in the future.

One goal of the NOMEC Strategy is to build public and private partnerships to map, explore, and characterize the U.S. ocean and coastal waters (including the Great Lakes).[76] Fulfilling this goal may help accelerate the analysis of bathymetric data needed to completely map U.S. ocean and coastal waters. In 2021, NOAA announced the creation of the Brennan Matching Fund (BMF) to encourage nonfederal entities to partner with NOAA to acquire more ocean and coastal survey data,[77] and in 2022, the BMF was enacted (P.L. 117-263).[78] In FY2023, NOAA accepted two BMF projects. One partnership with the State of Connecticut Department of Energy aims to use multibeam and backscatter approaches to identify potential constraints for the installation of offshore wind electric transmission cables. The second partnership, with the Cordova, AK, Electric Cooperative, aims to use lidar to support the laying of an undersea power cable to a regional Federal Aviation Administration flight station.[79] Congress may consider whether to provide increased funding support to enhance public-private partnerships aimed at collecting and analyzing new bathymetric data, or funding support for the integration of existing modern bathymetric data from multiple sources (e.g., federal, state, academic, nongovernmental organizations).

Marine Geologic Hazards

Seafloor mapping is a primary tool used for seafloor geohazard assessments. Congress may wish to consider using these assessments to inform decisions about national security, such as protecting coastal communities. Improved scientific knowledge of marine geohazard events (e.g., earthquakes, tsunamis, marine landslides) can help safeguard coastal communities and marine infrastructure (e.g., pipelines, undersea cables). Detailed imaging of the seafloor can provide information about the complex seafloor landscape, such as how fast a seafloor fault is moving and when the last earthquake occurred along that fault.[80] For example, the Cascadia subduction zone off the coast of the northwestern United States has the capability of producing earthquakes of

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[72] P.L. 111-11, Title XII, Part II, Subtitle B.

[73] Ocean Science and Technology Subcommittee of the Ocean Policy Committee, *National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone*, June 9, 2020. Hereinafter referred to as *NOMEC Strategy*, 2020, pp. 1-20.

[74] Email correspondence with NOAA, Congressional Affairs Specialist, Office of Legislative and Intergovernmental Affairs, January 14, 2022.

[75] Ibid.

[76] *NOMEC Strategy*, 2020, pp. 17-19.

[77] For example, NOAA, "Notice of Matching Fund Opportunity for Ocean and Coastal Mapping and Request for Partnership Proposals," 87 *Federal Register* 35509, June 10, 2022.

[78] P.L. 117-263, Division J, Title CIII, Sec. 12206.

[79] Email correspondence with NOAA, Congressional Affairs Specialist, Office of Legislative and Intergovernmental Affairs, April 14, 2023.

[80] USGS, "Marine Geohazards," May 6, 2022, https://www.usgs.gov/media/slideshows/marine-geohazards.

magnitude 8 or 9, which could cause destructive tsunamis that would strike the coastlines of Washington, Oregon, and Northern California.[81] Knowledge of this subduction zone allows for the establishment and enforcement of construction standards for marine infrastructure that can withstand seafloor movement, which aims to save lives and mitigate potential damage and the need for costly repairs.

Congress also may wish to use data of seafloor hazards to inform funding level decisions for federal programs aimed at preparing communities for marine geohazard events. For example, the National Weather Service National Tsunami Hazard Mitigation Program provides grants to partner states for tsunami-related activities, such as preparing evacuation plans and maps,[82] and the Federal Emergency Management Agency Building Resilient Infrastructure and Communities grant program funds the construction of tsunami vertical evacuation towers.[83] In addition, the National Tsunami Warning Center and the Pacific Tsunami Warning Center monitor for tsunamis and the earthquakes that cause them and issue tsunami alerts to coastal communities.[84]

Environmental Protection of the Deep Sea

Congress may consider using maps identifying certain marine habitats to establish marine protected areas or to weigh the potential ecological impacts associated with natural resource exploitation. In 2017, NOAA's *Okeanos Explorer* concluded a three-year field campaign mapping approximately 600,000 square kilometers of the Pacific seafloor (about 61% within the U.S. exclusive economic zone, or EEZ) and documenting its biodiversity.[85] Knowledge and understanding of the U.S. deep sea through exploration and scientific research may allow for protection of certain habitats and establishment of a domestic supply of marine natural resources, such as critical minerals, located in the U.S. EEZ. In addition, the documentation of deep-sea habitats can provide baselines for understanding whether and how vulnerable (or resilient) they might be to human disturbance or natural environmental change. Congress may consider the level of funding to provide to support NOAA's deep-sea exploration campaigns that are designed to better explore and characterize the ocean.[86]

Seabed Mineral Resource Deposits

Congress has interest in securing and enhancing the domestic supply of critical minerals. Bathymetric and G&G survey data can help identify potential deep-sea mineral resource deposits,

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[81] NOAA, "JetStream Max: Cascadia Subduction Zone," https://www.noaa.gov/jetstream/jetstream-max-cascadia-subduction-zone#.

[82] National Weather Service (NWS), "NOAA/NWS Tsunami Activities Grants – Allowable Grant Activities," https://nws.weather.gov/nthmp/grants/Allowable.pdf.

[83] For example, see FEMA, "Shoalwater Bay Tribe Builds Evacuation Tower to Provide Tsunami Safety for Community," June 30, 2021, https://www.fema.gov/blog/shoalwater-bay-tribe-builds-evacuation-tower-provide-tsunami-safety-community.

[84] NWS, "Detection, Warning, and Forecasting," https://www.weather.gov/jetstream/tsu_detect.

[85] Brian R.C. Kennedy et al., "The Unknown and the Unexplored: Insights into the Pacific Deep-Sea Following NOAA CAPSTONE Expeditions," in *Frontiers in Marine Sciences*, vol. 6 (August 2019), p. 2.

[86] NOAA's Office of Marine and Aviation Operations operates oceanographic research vessels (e.g., *Okeanos Explorer*) that help achieve the Administration's scientific missions. NOAA's Office of Oceanic and Atmospheric Research Deep-Sea, which houses the Office of Ocean Exploration and Research, owns the mission equipment onboard the *Okeanos Explorer* and coordinates the ship's exploration mission. NOAA, "About NOAA Ship *Okeanos Explorer*," https://oceanexplorer.noaa.gov/okeanos/about.html.

such as ferromanganese crusts, which may contain cobalt, manganese, and rare earth elements.[87] For example, bathymetric data can identify geologic features such as seamounts, where ferromanganese crusts often can be found on their summits and flanks.[88] Congress may be interested in interagency coordination of seabed mining research activities by NOAA,[89] USGS,[90] and BOEM,[91] among others, to better document the distribution seabed minerals in the U.S. EEZ and in areas beyond national jurisdiction. In addition, Congress may consider directing these agencies to coordinate research activities to study potential seabed mining impacts on deep-sea habitats. For example, the 117th Congress considered legislation that would have called on the NOAA Administrator to seek "an agreement with the National Academies to conduct a comprehensive assessment of the environmental impacts of deep-sea mining."[92] Congress may consider using maps that identify certain marine habitats to establish marine protected areas that limit (or restrict) exploitation activities, or to weigh the potential ecological impacts associated with the seabed mining in these habitats.

[87] USGS, "Global Marine Mineral Resources," https://www.usgs.gov/centers/pcmsc/science/global-marine-mineral-resources?qt-science_center_objects=0.

[88] For more information on the occurrence of seabed minerals, see CRS Report R47324, *Seabed Mining in Areas Beyond National Jurisdiction: Issues for Congress*, by Caitlin Keating-Bitonti.

[89] NOAA implements the Deep Seabed Hard Mineral Resources Act (P.L. 96-283; 30 U.S.C. §§1401-1473), enacted in 1980, which governs seabed mining activities in areas beyond national jurisdiction.

[90] The Global Marine Mineral Resources Project, based out of the USGS Pacific Coastal and Marine Science Center, "provide[s] stakeholders with the best available science regarding potential resources and environmental impacts associated with accessing [marine mineral deposits]." USGS, "Global Marine Mineral Resources," https://www.usgs.gov/centers/pcmsc/science/global-marine-mineral-resources?qt-science_center_objects=0.

[91] OCSLA authorizes the Department of the Interior (DOI) to manage the submerged lands of the OCS (43 U.S.C. §§1331-1356c). DOI delegated the mineral leasing authorities to BOEM. BOEM scientists use the results of environmental studies to characterize the effects of proposed mineral extraction from the OCS and design mitigation measure to minimize or avoid adverse effects. BOEM, "Research and Studies," https://www.boem.gov/marine-minerals/research-and-studies.

[92] In the 117th Congress, H.R. 3764.

Appendix A. Background on Selected Physical Oceanographic Variables

Ocean Temperature

Ocean temperature varies predictably—colder water occurs at higher latitudes and at greater depths, as well as in regions where wind energy pushes sea surface water in a specific direction, allowing for deep water to move to the surface (see text box entitled "Ocean Upwelling"). Sea surface temperatures (SSTs) and temperatures for water depths up to 2,000 meters are primarily collected by National Oceanic and Atmospheric Administration (NOAA) Argo Profiling Floats.[93] As Argo floats drift in the ocean and submerge to new pressure levels at different water depths, they collect data on the water's temperature profile (**Figure 1**). When Argo floats return to the surface, they transmit temperature data via satellites to scientists for processing and analysis.

Various instruments other than Argo floats also collect and transmit ocean temperature data. Research vessels can collect ocean temperature and other data using deployable vehicles or devices. For example, unmanned wave gliders are remotely operated vehicles that collect SST data. Research vessels can also deploy Conductivity, Temperature, and Depth (CTD) sensors that collect water temperatures at various water depths. Wave gliders and CTD sensors are limited to the path taken by the ship, but can provide detailed data for specific sites.

The satellites Aqua, Terra, Suomi National Polar-Orbiting Partnership (NPP), and NOAA-20 are equipped with instruments that collect near-global SST data from space. Unlike sensors deployed in the ocean, they collect data from the top 1 millimeter of the ocean.

Over the 20th century and continuing today, global SSTs have increased as the ocean absorbs more heat.[94] Ocean temperature impacts global climate. For example, warm waters increase the amount of water vapor over the ocean that can influence weather systems (e.g., precipitation patterns, storm events).[95] Warming SSTs also have the potential to affect marine ecosystems by altering where species can live and when species migrate and reproduce, and causing loss of life for species that cannot migrate to new waters.[96] Additionally, ocean temperature influences other ocean variables, such as ice, sea level (because of thermal expansion of ocean water),[97] chlorophyll, dissolved oxygen, and pH.

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[93] Sea surface temperatures (SSTs) are considered as depths up to 5 meters below the surface ocean. NOAA, "Argo Center," https://www.aoml.noaa.gov/phod/argo/.

[94] EPA, "Climate Change Indicators: Sea Surface Temperature," https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature.

[95] NASA, "Sea Surface Temperature & Water Vapor," https://earthobservatory.nasa.gov/global-maps/MYD28M/MYDAL2_M_SKY_WV.

[96] "Chapter 5. Changing Ocean, Marine Ecosystems, and Dependent Communities," in IPCC, *Ocean and Cryosphere*.

[97] Because water expands as it warms (thermal expansion), warming ocean water causes sea level rise.

Ocean Upwelling

There are two types of ocean upwelling.

- **Coastal upwelling** is the most common type of upwelling and generally occurs along the western coast of North America in the winter and year-round along the western coasts of South America and Africa. In the winter, strong winds typically blow north to south along the west coast of the United States. Due to Earth's rotation, these strong winds cause surface waters along the western U.S. coast to be pushed offshore, allowing for deep, colder ocean waters to replace them. This path of air deflection is called the *Coriolis Effect*. Because of the *Coriolis Effect*, surface ocean water is also deflected, moving at about 90-degrees to the right of the wind direction in the Northern Hemisphere and about 90-degrees to the left of the wind direction in the Southern Hemisphere. This movement of water is called *Ekman Transport* (or *Ekman Spiral*).
- **Equatorial upwelling** occurs along the equator. Surface water in the Northern Hemisphere diverges northward along the equator (to the right) and southward in the Southern Hemisphere (to the left) due to the *Coriolis Effect*. Where these two surface water masses diverge away from each other along the equator, deep, colder waters rise to the surface. Trade winds in the Indian Ocean make equatorial upwelling less prevalent in this ocean basin compared to the Atlantic and Pacific Oceans.

Sources: National Oceanic and Atmospheric Administration (NOAA), "The Coriolis Effect," https://oceanservice.noaa.gov/education/tutorial_currents/04currents1.html; NOAA, "The Ekman Spiral," https://oceanservice.noaa.gov/education/tutorial_currents/04currents4.html.

Ice

Continental ice and sea ice cover vast swaths of the Antarctic and Arctic regions, including Greenland. Extreme weather, ice-covered terrain, and thick sea ice can pose challenges to research vessel polar scientific expeditions. Satellite and aircraft remote sensing allow for more continuous and broad monitoring of these regions, including aspects such as ice thickness and areal extent. Sea-ice concentration data are derived from the Advanced Topographic Laser Altimeter System on the IceSat-2 and the Special Sensor Microwave/Imager and Special Sensor Microwave Imager/Sounder on Defense Meteorological Satellite Programs satellites.[98] The VIIRS instrument onboard both the Suomi NPP and NOAA-20 also collects data used to monitor the amount of ice at the poles. The GRACE-FO satellite measures changes to Earth's gravitational pull, which reflect changes in Earth's distribution of mass (including water and ice).[99] As ice melts and redistributes water across the planet, it alters Earth's gravitational pull, allowing scientists to use the satellite data to measure these water mass and ice mass changes.

Continental and sea-ice melt add freshwater to the surface ocean. Freshwater is less dense than seawater and consequently tends to layer with the underlying seawater, leading to the stratification of ocean water in regions with increased ice melt. Cold, salty polar surface waters are dense enough to sink to depth in the ocean and fuel global deep-sea circulation. Because cold water also holds more dissolved gasses than warm water, polar regions play an important role in absorbing atmospheric CO_2 and sinking this carbon into the deep ocean.

Sea Level

The global average sea level has been slowly rising because of melting continental ice and thermal expansion of ocean water due to its warming. The surface height (elevation) of the ocean

[98] Initiated by the Department of Defense in the mid-1960s, the Defense Meteorological Satellite Program is composed of low, Earth-orbiting satellites that provide the military with environmental information. These satellites provide global coverage twice per day. Meteorologists interpret the data (e.g., cloud type, land and water temperatures, water currents) for U.S. military operations worldwide.

[99] NASA, "GRACE, GRACE-FO Satellite Data Track Ice Loss at the Poles," March 18, 2020, https://climate.nasa.gov/news/2959/grace-grace-fo-satellite-data-track-ice-loss-at-the-poles/.

in any particular area can naturally vary in places due to gravitational pull from the moon and sun, Earth's rotation, atmospheric pressure, and gravitational forces from continental land mass.[100]

Satellite-based radar altimeters measure variations in the surface height of the ocean by sending pulses of microwaves toward the ocean that bounce off its surface and return to the satellite. Similar to sonar sensor systems, the amount of time it takes for the signal to return to the satellite corresponds to the height of the sea surface. Both Jason-3 and Sentinel-6 Michael Freilich are altimetry satellites. The Jason-3 satellite is a shared partnership between NASA, NOAA, France's Centre National d'Etudes Spatiales, the European Organisation for the Exploitation of Meteorological Satellites, and the European Space Agency.[101] The Sentinel-6 Michael Freilich satellite is a collaborative partnership between the European Space Agency, European Commission, European Organisation for the Exploitation of Meteorological Satellites, SpaceX, NASA, and NOAA.[102] The GRACE-FO satellite measures changes to Earth's gravitational pull, which can provide information about the amount of sea level rise as the distribution of water and ice changes across Earth's surface.[103]

Prior to altimetry satellites, tide gauges were used to continuously collect tidal wave heights. This recorded the height of the surrounding water relative to a reference point, taking into account land elevation changes. Modern gauges use a microprocessor-based technology to collect sea level data every six minutes and are synchronized with Geostationary Operational Environmental Satellites.[104]

Heating of Earth's climate system has led to both continental ice melt and thermal expansion of the ocean, leading to global mean sea level rise.[105] Due to sea level rise, low-lying areas are susceptible to more frequent and severe coastal flooding events and sandy coastlines more susceptible to coastal erosion. The 2021 IPCC *Sixth Assessment Report* also projects that with high confidence that extreme sea level events that previously occurred once per century at least annually at more than half of all tide gauge locations by 2100.[106]

Chlorophyll (Ocean Color)

The chlorophyll concentration of the surface ocean provides an estimate for living phytoplankton in the near-surface water and is inversely correlated with temperature (i.e., dense populations of phytoplankton occur in cold surface waters where ocean upwelling has occurred).[107]

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[100] NASA, "Sea Level 101: What Determines the Level of the Sea?," June 3, 2020, https://climate.nasa.gov/ask-nasa-climate/2990/sea-level-101-what-determines-the-level-of-the-sea/.

[101] NOAA, "Taking a Measure of Sea Level Rise: Ocean Altimetry," https://earthobservatory.nasa.gov/images/147435/taking-a-measure-of-sea level-rise-ocean-altimetry.

[102] Linda Herridge, "Sentinel-6 Michael Freilich Satellite in Earth Orbit, Mission Begins to Map Sea Levels," *NASA Blogs*, November 21, 2020, https://blogs.nasa.gov/sentinel-6/.

[103] NASA, "Sea Level," https://gracefo.jpl.nasa.gov/science/sea-level/.

[104] Geostationary Operational Environmental Satellites (GOES) track the same position on Earth's surface as the planet rotates, thereby providing constant surveillance over the specified area. These satellites can provide information on weather conditions (e.g., tornados, floods, hurricanes). NASA, "GOES Satellite Network," https://www.nasa.gov/content/goes; and NOAA, "What Is a Tide Gauge?" https://oceanservice.noaa.gov/facts/tide-gauge.html. For more information, see CRS Report R44632, *Sea-Level Rise and U.S. Coasts: Science and Policy Considerations*, by Peter Folger and Nicole T. Carter.

[105] "Summary for Policymakers," in IPCC, *AR6 Physical Science Basis*, p. SPM-14.

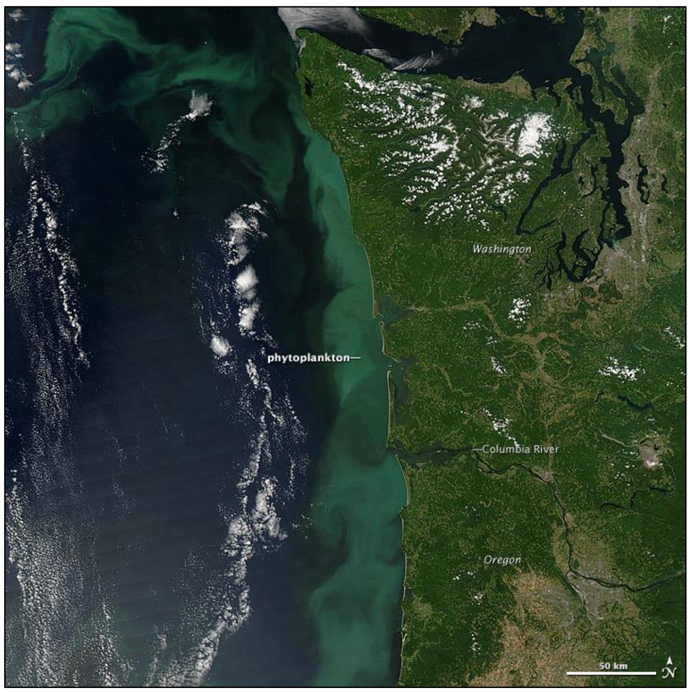
[106] Ibid, p. SPM-33.

[107] NASA, "Chlorophyll Concentration (1 Month—Aqua/Modis)," https://neo.gsfc.nasa.gov/view.php?datasetId=MY1DMM_CHLORA.

Phytoplankton use photosynthetic green pigments (chlorophyll) to convert the solar energy they capture into organic matter. When phytoplankton occur in dense populations, the color of the ocean appears greener (**Figure A-1**). The MODIS instrument on the Aqua and Terra satellites and the VIIRS instrument on the Suomi NPP and NOAA-20 satellites collect chlorophyll data.

Chlorophyll concentrations provide information about ocean health and primary productivity in surface waters. Deep, cold waters tend be nutrient-rich; when these waters are exposed to sunlight, marine phytoplankton absorb solar energy and atmospheric CO_2 to form organic matter, forming the base of the marine food chain for larger organisms to feed on them. Phytoplankton are composed of organic (flesh) and inorganic (shell) carbon; thus, when phytoplankton die, the inorganic shell of the organism sinks to depth in the ocean, removing carbon from the surface waters. This process provides a natural atmospheric CO_2 sink.

Figure A-1. Phytoplankton Bloom off the Washington Coast



Source: National Aeronautics and Space Administration (NASA) Earth Observatory, https://earthobservatory.nasa.gov/images/84095/phytoplankton-bloom-off-the-pacific-northwest.

Notes: NASA's Aqua satellite captured this image of coastal upwelling on July 26, 2014. Upwelling currents and summer weather promoted this large phytoplankton bloom off the Pacific Northwest making the coastal ocean waters appear green.

Seafloor Bathymetry

An estimated 77% of the global ocean remains unmapped.[108] The primary instrument used for mapping the seafloor is a multibeam sonar sensor, which attaches directly to a ship's hull. A multibeam sonar sensor sends out simultaneous sonar beams (sound waves) in a fan-shaped pattern to collect seafloor information surrounding the ship.[109] The amount of time it takes for the

[108] The Nippon Foundation-GEBCO Seabed 2030 Project, "Mapping Progress," https://seabed2030.org/mapping-progress.

[109] A single-beam sonar uses only one sonar beam aimed directly beneath the ship to collect bathymetric data.

sonar sound wave to return back to the sensor corresponds to the depth of the seafloor. Multibeam sonar sensors also can collect backscatter measurements, which correspond to the return beam's intensity. The return signal's intensity provides information about the seafloor's composition; for example, a mud surface absorbs most of the sound pulse, returning a weak signal to the receiver, whereas a rocky surface absorbs little of the sound pulse, returning a strong signal.[110]

A sidescan sonar also provides information on the composition of the seafloor sediment. This equipment, which is towed off vessels on long cables, sends and receives sound signals across the seafloor, recording the return signal's intensity.

Satellite-based remote sensing technology can also be used for shallow seafloor mapping, especially in areas inaccessible to research vessels. The Landsat 8 and Landsat 9 satellites provide near-shore bathymetric data, but the satellite primarily collects land-based observations for a variety of governmental and nongovernmental applications.[111] The ICESat-2 satellite is equipped with lidar technology that can be used to map coastal waters.[112]

Knowledge of seafloor bathymetry serves several navigation, economic (marine resources), and ocean science purposes. Nautical charts are based on bathymetric data. Characteristics of the seafloor partially derived from bathymetric data can help identify and locate natural resources of economic value (e.g., sand and gravel, critical minerals, oil and gas reserves). In addition, seafloor characteristics can help study changing coastlines (e.g., erosion, land sinking), geologic hazards (e.g., active faults), and the habitats of benthic organisms (i.e., organisms living on or in seafloor sediments).

[110] NOAA, "Sea Floor Mapping," https://oceanexplorer.noaa.gov/explorations/lewis_clark01/background/seafloormapping/seafloormapping.html.

[111] USGS, "Satellite-Derived Bathymetry," https://www.usgs.gov/special-topics/coastal-national-elevation-database-%28coned%29-applications-project/science/satellite; NASA, "Landsat 8 Mission Details," https://landsat.gsfc.nasa.gov/satellites/landsat-8/landsat-8-mission-details/. For more information, see CRS Report R46560, *Landsat 9 and the Future of the Sustainable Land Imaging Program*, by Anna E. Normand.

[112] NASA, "Sounding the Seafloor with Light," https://earthobservatory.nasa.gov/images/148246/sounding-the-seafloor-with-light.

Appendix B. Background on Selected Biogeochemical Oceanographic Variables

Salinity

Salinity (saltiness) is a measure of the dissolved salt ions in seawater. The two most common ions in seawater are chloride and sodium. They make up over 90% of all dissolved ions in seawater. Dissolved ions can be washed from land into the ocean via rivers or can be mixed into seawater by submarine hydrothermal vents or undersea volcanoes.[113] Salinity can be measured using Argo floats; unmanned wave gliders; Conductivity, Temperature, and Depth (CTD) sensors; and water quality gauges.

Salinity and sea surface temperature determine the density of surface ocean water. Density differences between water masses (e.g., surface water versus deep-sea water) drive ocean circulation, which is the primary mechanism for transporting heat across and within the global ocean. Scientists use the salinity of ocean water to trace ocean circulation patterns and to monitor freshwater input from land or melting ice. Both increased precipitation over land and continental and sea-ice melt are freshening near-surface ocean waters,[114] which may contribute to weaker ocean circulation.

Dissolved Oxygen

Dissolved oxygen is the amount of oxygen that is present in water.[115] The amount of dissolved oxygen is affected by seawater temperature, patterns of ocean circulation, ocean mixing (driven by wind energy and ocean stratification), aerobic biological activity (i.e., respiration), and distance from oxygen source (e.g., depth from the interface between the surface water and the atmospheric). Continental runoff with increased nutrient loads (e.g., fertilizer) or pollution (e.g., wastewater) can lead to excessive richness of nutrients in the water. This may stimulate marine algal blooms that lower the amount of dissolved oxygen.[116] Dissolved oxygen concentrations can be measured using Argo floats, unmanned wave gliders, and water quality gauges.

Because warm water holds less dissolved gas compared to cold water, the ocean is holding less dissolved oxygen as a result of global ocean warming.[117] Many marine species have undergone shifts in geographic range and seasonal changes in response to oxygen loss, in addition to other oceanographic changes, which may affect the aquaculture sector.[118]

[113] USGS, "Why Is the Ocean Salty?" https://www.usgs.gov/special-topic/water-science-school/science/why-ocean-salty?qt-science_center_objects=0.

[114] "Summary for Policymakers," in IPCC, *AR6 Physical Science Basis*, p. SPM-6.

[115] EPA, "Indicators: Dissolved Oxygen," https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen.

[116] For more information on harmful algal blooms, see CRS Report R46921, *Marine Harmful Algal Blooms (HABs): Background, Statutory Authorities, and Issues for Congress*, by Eva Lipiec.

[117] T.L. Frölicher et al., "Contrasting Upper and Deep Ocean Oxygen Responses to Protracted Global Warming," *Global Biogeochemical Cycles*, vol. 34 (August 2020), p. 1.

[118] "Summary for Policymakers," in IPCC, *Ocean and Cryosphere*, p. SPM-12.

pH

The ocean's surface is in chemical equilibrium with Earth's atmosphere—as atmospheric CO_2 concentrations increase, surface ocean water absorbs more CO_2. When atmospheric CO_2 dissolves into the ocean, it forms carbonic acid. Some of the carbonic acid dissociates in ocean waters, producing hydrogen ions. As the number of hydrogen ions increases, the pH of seawater decreases and the seawater becomes more acidic, a process known as *ocean acidification*.[119] The NOAA Ocean Acidification Program uses two types of floating devices—moored (stationary) buoys and wave gliders—that measure the concentration of dissolved CO_2 every three hours.[120] Scientists use the data collected by these devices to study the rate of carbon uptake by the ocean.

More acidic waters can physiologically stress some marine invertebrate organisms (e.g., clams, snails, crabs) that use carbonate ions to create their shells, which result in a less robust carbonate shell and might make the organisms more susceptible to predation and death.[121]

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[119] For more information on ocean acidification, see CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec.

[120] NOAA, "Monitoring," https://oceanacidification.noaa.gov/WhatWeDo/Monitoring.aspx.

[121] Smithsonian, "Ocean Acidification," https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification.