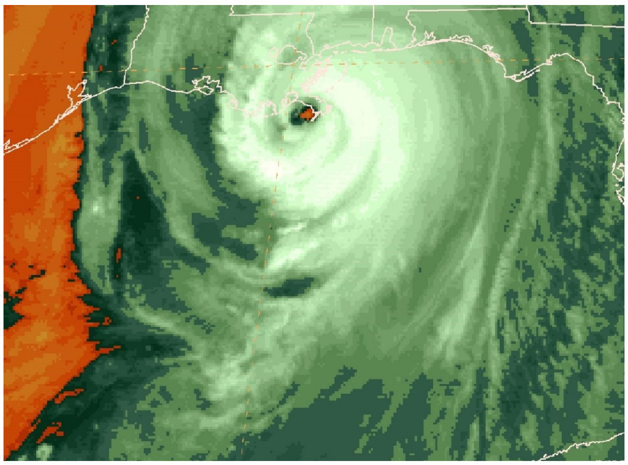
Hurricane activity is increasing in the North Atlantic


Computer image of Hurricane Katrina. Credit: Jeff Weber, UCAR

Analyses of hurricane strength historical records from the North Atlantic have suggested that, over the past 150 years, the frequency of these storms has increased. Some have criticized this research, stating that problems with historical record-keeping are responsible for the increasing trend, rather than an actual increase.

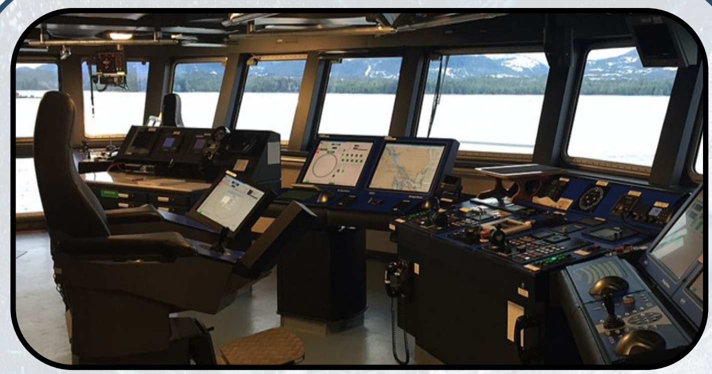
A new study using computer modelling of storm frequency, by NSF-supported scientist Dr. Kerry Emanuel of MIT, backs up the historical data.

The modelling used sea surface temperature and pressure data to recreate historical hurricane patterns, and, although the study did suggest that the frequency of historical hurricanes in the 19th century may have been undercounted, nevertheless there has still been a trend of increasing hurricane frequency in the North Atlantic.

In addition, in the 20th and 21st centuries, there was an increasing trend in hurricane power—this increase in hurricanes' destructive potential is a cause for concern. The increase in hurricane frequency was linked to changes in regional climate and, considering the current increasing temperature trends in the North Atlantic, there is likely to be a continuing increase in hurricane frequency and power in this region.

Paper: https://www.nature.com/articles/s41467-021-27364-8

Grant: ICER-1854929



A view from the bridge

The ocean connection

We live on a blue planet, where the ocean covers over 70 percent of the surface. Moreover, human beings owe their life to the sea. For example, four in 10 humans rely on the ocean for food, phytoplankton produce most of the oxygen we breathe, and the ocean regulates the planet's water cycle and stores enormous amounts of carbon and heat. In fact, the ocean has absorbed over 90 percent of the heat added to the climate system since the 1970's. The ocean-climate system is inherently interconnected and interwoven, much like a braided rope. Indeed, the fate of humanity is interconnected with that of the ocean—it is hard to overstate the importance of the ocean to society and our lives.

Oceans are home to tremendously diverse ecosystems, from coral reefs and coastal salt marshes to the deep ocean. Scientists have described nearly a quarter of a million ocean species, but this is believed to be just the tip of the iceberg when it comes to ocean biodiversity, with an estimated ten times that number yet to be described. This biodiversity is essential for the functioning of ocean biological systems, but these diverse ecosystems also support the well-being of many human communities. For example, mangroves and coral reefs help stabilize coastlines and prevent shoreline erosion. They also provide vital habitat for species targeted in commercial and recreational fisheries. NSF funds researchers to explore how ocean biodiversity can be maintained and the factors that influence how resilient some organisms are to climate change stress.

Continued on next page...

The planet's changing climate and ocean systems are having significant societal impacts, *inter alia* on food security, human health, global commerce, sustainable coastal communities, human migrations, and human safety. NSF facilitates the generation of knowledge that is fundamental to our understanding of the interconnections between the oceans and humans, and to the development of innovative ways to utilize our oceans more sustainably.

Research and technology

Research and technology development are vital to understanding the climate processes taking place in the ocean and how they are changing over time. Understanding ocean dynamics requires the integration of knowledge in biology, chemistry, physics, and geology. Studying the marine carbon cycle is an example of such integration in action. NSF funds research that examines how, why, and where the ocean absorbs carbon from the atmosphere, where that carbon moves over time, and how it impacts marine ecosystems. This work is vital for understanding the ocean's capacity to continue to absorb human-produced greenhouse gas emissions.

Moreover, long-term research programs, which collect and organize the same types of data over time, are vital to get an accurate picture of how the ocean works. For example, NSF funds Long-Term Ecological Research Sites—many of these sites conduct research related to the ocean or coasts. We can document and analyze conditions and changes in the ocean over time, due to investment in sensor and technology development. Such research identifies climate and other environmental changes that short-term studies might miss.

NSF also supports active examination of the ocean environment via the vessels (and the sensors they carry) in the U.S. Academic Research Fleet. The Fleet provides the capacity to investigate ocean environments that scientists might otherwise be unable to access. NSF also funds state-of-the-science ocean observations via programs such as the various ocean sensor systems supported by the Ocean Observatories Initiative (OOI). Understanding the ocean's roles in our planet's climate system is vital for understanding the impacts and implications of climate change-driven shifts in our oceans.

The impacts of climate change

Long-term investment in basic research, as noted above, helps us understand how climate change is affecting the oceans and people. Rising global temperatures are causing drastic environmental

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Whale distributions shift due to climate change faster than expected

Researchers have assumed that warm-blooded marine mammals would be less affected by changing water temperatures compared to their cold-blooded prey. However, a new study by NSF-funded researchers investigated the effect of climate change on the movement of long-finned pilot whales, and their prey, over a 25-year period. The distribution of whales in the waters of the northeastern U.S. shifted northwards as ocean temperatures rapidly warmed, but surprisingly the distribution of the whales shifted at three times the rate of their fish and squid prey species, in response to climate change. The shifts in the distribution of the whales were correlated with sea surface temperatures rather than shifts in prey distribution and this may have major implications for food web ecology and ecosystem structure.

Paper: **https://www.nature.com/articles/s41598-021-97318-z**

Grant: OCE-1851898

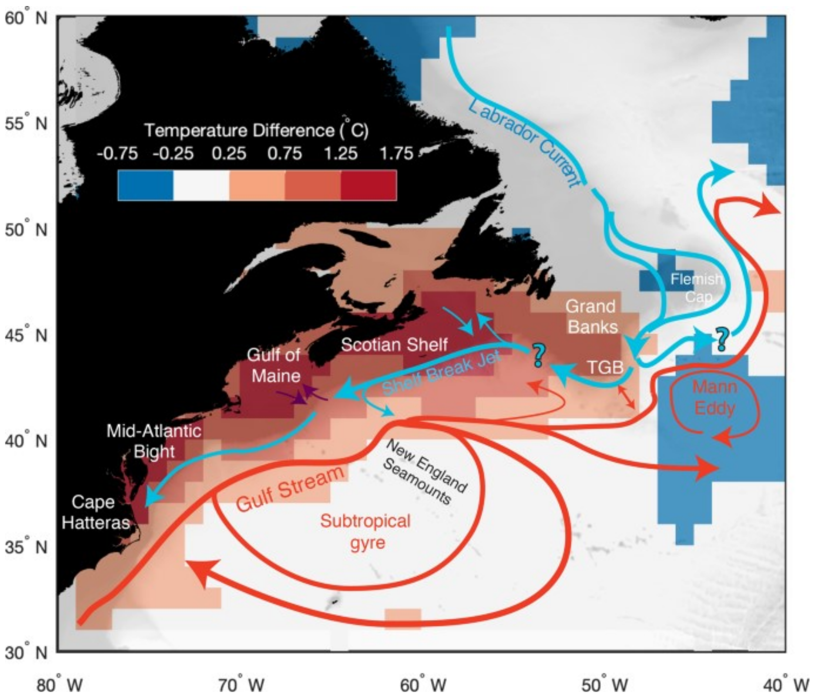
A pilot whale Credit: Chris Parsons, NSF

Gulf Stream migration makes Northwest Atlantic one of the fastest warming ocean regions

The Northwest Atlantic Shelf is experiencing marine heat waves, changes in fisheries, and a surge in sea level rise. This is an area inhabited by many vulnerable species, most notably the endangered North Atlantic right whale, and important fisheries. Satellite data were used to show that when the Gulf Stream migrates closer to the underwater plateau of the Grand Banks (Newfoundland), it blocks the southwestward flow of the Labrador Current, which would bring water that is less saline, colder, and more oxygen-rich to the North American shelf. The most recent decade has been the hottest on record at the edge of the Northeast United States and Canada, because the presence of the Gulf Stream prevented the inflow of this cooler water. By monitoring the flow of these currents (via satellite), it may be possible to predict potential impacts on this area's marine ecology.

Paper: https://doi.org/10.1038/s43247-021-00143-5

Grant: OCE-1947829



Circulation in the Northwest Atlantic Ocean and the water column average temperature difference between the period 2009–2018 and 2001–2007. From Gonçalves Neto *et al.* 2021

Water runoff from melting ice is bringing more carbon and nutrients into the Arctic

Researchers with the NSF-funded GEOTRACES program have discovered that increasing levels of fresh-water runoff, due to melting ice, are bringing higher levels of carbon and trace elements into the waters of the Arctic Ocean. Because this runoff is being bound to organic matter from the land surface and rivers, it is allowing carbon and trace elements to be transported over 1000km from their source into central Arctic waters. Some of these trace elements, such as iron, are a limiting nutrient in ocean waters, and elevated levels lead to an increase in ocean productivity and algal growth. However, some trace elements, such as mercury, are toxic to marine ecosystems. These increases in carbon and trace elements could contribute to changing Arctic ecosystems.

Paper: https://doi.org/10.1029/2019JC015920

Uncovering the diversity of RNA viruses in the ocean

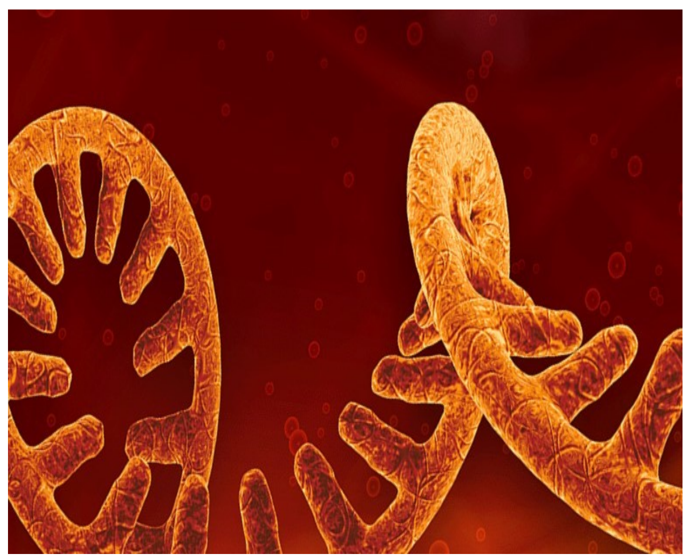
A recent global survey of the ocean has dramatically increased our knowledge of RNA viruses. A total of 35,000 ocean water samples were collected. By combining machine-learning analyses with traditional methods, NSF-funded researchers have identified 5,500 new RNA virus species and expect at least five new RNA virus phyla to accommodate these new species.

"There's so much new diversity here—and an entire phylum, the *Taraviricota* [named after the research vessel], was found all over the oceans, which suggests they're ecologically important," said Dr. Michael Sullivan of Ohio State University, the study's lead author. "RNA viruses are clearly important in our world, but we usually only study a tiny slice of them—the few hundred that harm humans, plants and animals."

These researchers recently discovered that viruses play an important role in the biological pump that circulates and stores carbon in the ocean. As the ocean absorbs half of the human-generated carbon dioxide from the atmosphere, identifying these virus species is important beyond identifying ocean virus diversity.

Paper: https://www.science.org/doi/10.1126/science.abm5847

Grants: OCE-1829831; BII EMERGE -2022070



Credit: CROCOTHERY - stock.adobe.com

A computer generated image of RNA

Ozone may be heating the planet more than we realize

A new NSF-funded project has revealed that changes to ozone were responsible for almost a third of the warming seen in ocean waters around Antarctica during the second half of the last century. Researchers used models to simulate changes in ozone levels between 1955 and 2000, and found that a decrease in ozone in the upper atmosphere (due to damage caused by chlorofluorocarbons (CFCs), gases used in industry and aerosol sprays) and an increase in the lower atmosphere (the result of pollution from car traffic, power plants, and industry) contributed to warming seen in Sothern Ocean waters. The warming effect from ozone was far more than previously thought.

Paper: https://doi.org/10.1038/s41558-022-01320-w

Grant: OCE-2123422

Documenting a volcanic eruption

On 15 January 2022, the Hunga Tonga-Hunga Ha'apai volcano erupted near Tonga, spewing out a 58 km high volcanic plume—half way to space! This was the largest volcanic eruption since Mount Pinatubo in 1991 and the plume was twice the height of the Mount St. Helens eruption in 1989, which had been the record holder until then. NSF-funded scientists have documented this eruption, including tsunamis, volcanic lightning, and atmospheric waves that passed around the world. The amount of lightning associated with the eruption was staggering—for 2 hours, 80% of all the lightning strikes on Earth were in the sky above the volcano.

The researchers believe vaporizing seawater from the ocean island volcano—which quickly sank below the sea and vaporized seawater above it—caused lava to shatter into microscopic ash particles. When the plume hit the upper atmosphere, the steam from the eruption froze into ice crystals. The motion, temperature change, and size of the particles generated incredible amounts of static charge that were released as lightning.

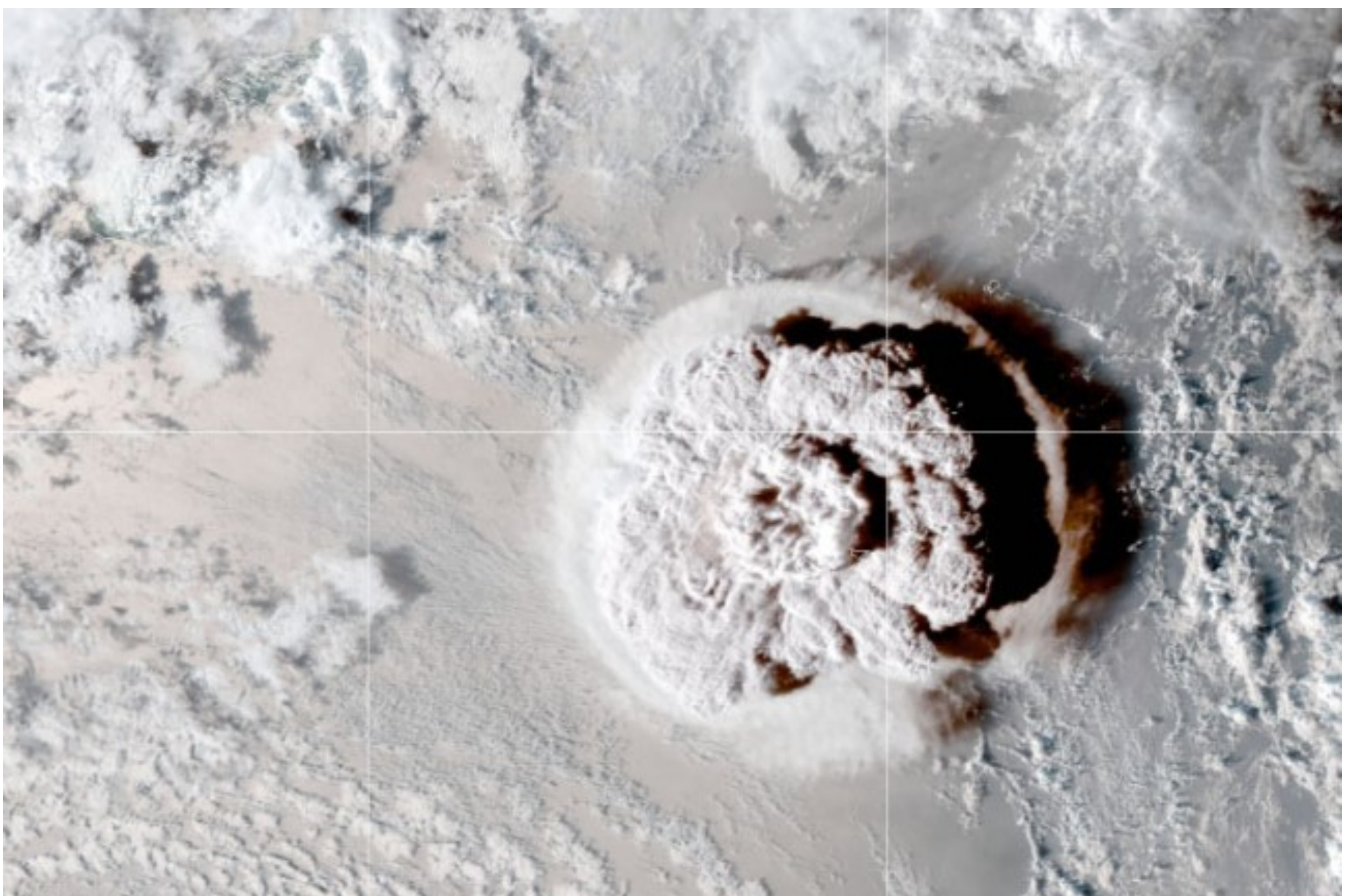
An estimated 1.9 km^3 of material was ejected by the eruption. This is sizeable, but not unique. What was unusual was how the eruption was able to transfer energy into the ocean and atmosphere, leading to tsunamis and atmospheric shock waves recorded around the world.

Paper: https://doi.org/10.1016/j.eqrea.2022.100134

Grant: OCE-1842989

OCE-funded researcher wins prestigious Waterman Prize

Dr. Jessica E. Tierney, a University of Arizona geoscientist funded by the Division of Ocean Science, is one of this year’s three winners of the prestigious Alan T. Waterman Award. The award is the Nation's highest honor for early-career scientists and it recognizes an outstanding early-career U.S. science or engineering researcher who demonstrates exceptional individual achievements. The award, established by Congress in 1975, is named after Alan T. Waterman, the first director of NSF. Awardees receive a medal and $1 million, over five years, to apply to their chosen research.



Credit: NASA Earth Observatory

Photo Credit: ASU

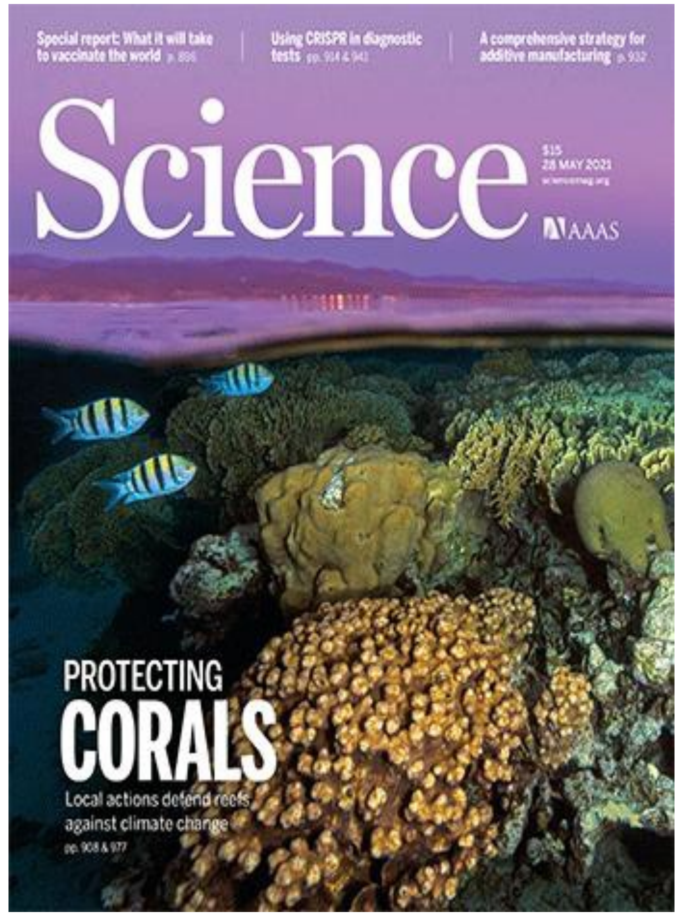
Dr. Tierney's research focuses on understanding how Earth's systems work through paleoclimatology—investigating ancient climates.

Dr. Tierney is recognized for her outstanding advances in the reconstruction of past climate change and furthering the understanding of future climate change. Her research involves analyzing organic chemicals in geological samples, which in turn give an indicator of historic temperatures and other climatic conditions. Her extrapolation of historical climate records to make predictions for the future led to her becoming a lead author on the 6^{th} Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Dr. Tierney is an alumna of the OCE Frontiers in Ocean Sciences symposium.

"It is an absolutely incredible honor to receive the Waterman Award," she said. "I'm really grateful to NSF for the support and I hope that my research will help society prepare for, and ultimately mitigate, human-caused climate change."

Caring for our reefs better may help them combat climate change

As ocean waters have warmed, corals have been one of the global victims. Increasing temperatures cause corals to expel their symbiotic algae. These algae give corals their distinctive color and, as the algae are lost, the corals "bleach." Diseases, pollution, smothering by fast growing macro-algae, and damage from storms, tourists, destructive fishing practices, and many other stressors are all negatively affecting reefs. As climate change is a global phenomenon, it takes global actions to reduce or reverse the emission of greenhouse gasses. These reductions have been slow and involve policies that must be enacted at the highest levels of government and



industry.

An NSF-funded study found that coral reefs where pollution, fishing, and other human impacts had been reduced were more resilient to the impacts of climate change. This is encouraging, as it means that local conservation action that reduces these stressors can help the survival of coral even in the face of rising global temperatures, until greenhouse gas levels in the atmosphere can be reduced.

Scientists, both professionals and trained citizens, collected data from 223 sites around the world on behalf of the charity "Reef Check." On analyzing the data, they found that local stressors could exacerbate coral loss in the year following a bleaching event. In particular, reefs with more seaweeds (macro-algae) had levels of coral mortality that were ten times higher—an effect that increased as temperatures rose. High levels of macro-algae are linked to overfishing and nutrient pollution. In addition, several coral diseases are also linked to nutrient pollution. Therefore, reducing these factors can help to reduce macro-algae levels and to make coral more likely to recover after bleaching events.

Paper: https://science.sciencemag.org/content/372/

Grants: OCE-1829393; OCE 1657633

Quieter oceans during the pandemic

Researchers monitoring underwater noise off the coast of Newport, Oregon, discovered that there was a large decrease in noise levels from shipping in 2020 during the COVID-19 pandemic. In fact, the amount of sound energy in the frequencies produced by shipping were about two-thirds what they averaged during the five years before the pandemic. The underwater noise data were recorded by the Regional Cabled Array network, which is part of the NSF-funded Ocean Observation Initiative (or OOI). In the second quarter of 2020, the number of ships entering Puget Sound decreased by 19% and the shipping containers declined by 17%, so the reduction in ocean noise aligns with a reduction in large shipping vessels. The researchers were also able to record fin whales within the vicinity of the array—these whales produce calls of similar frequencies to the sounds produced by large shipping vessels and thus may be affected by high levels of shipping noise.

Paper: https://doi.org/10.1121/10.0005192

Grant: OCE-1743430

Floodwater pollution affects reefs over 100 miles away

NSF-funded researchers have discovered that a Texas flood in 2016 and Hurricane Harvey in 2017 may have carried pollution over 100 miles offshore. Researchers examined sponges on the Flower Garden Banks Reef, located 100 miles off the coast of Texas and Louisiana, and found that *E. coli* and other bacteria in the sponges contained genetic markers that indicate the bacteria came from the floodwaters. It is known that nearshore reefs have been negatively affected by pollutants washed into the ocean by floods and runoff during rainstorms, but this study demonstrates that reefs a considerable distance offshore can also be affected by pollutants washed out to sea.

Paper: https://www.frontiersin.org/articles/10.3389/fmars.2021.608036/full

Grant: OCE-1800904; OCE-1800905; OCE-1800913; OCE-1800914

Photo Credit: NOAA

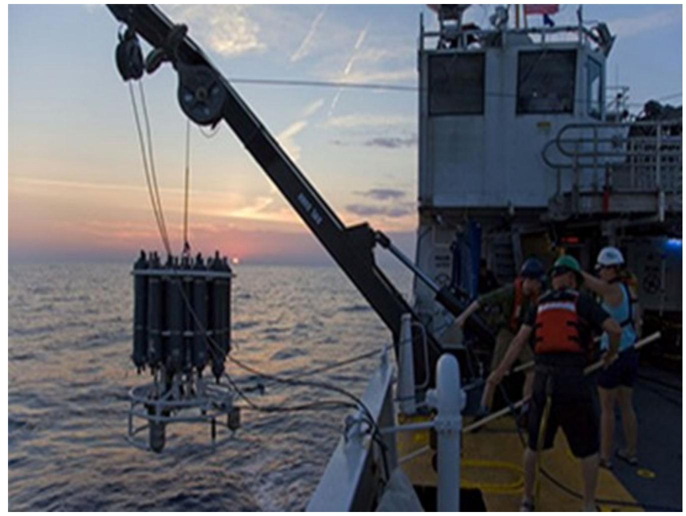


Photo Credit: Mark Sukel

The source of nitrogen nutrients in the Gulf of Mexico

NSF-funded researchers at Florida State University have discovered that almost all of the nitrogen in the Gulf of Mexico—an important nutrient for phytoplankton and therefore the food web—comes from coastal areas. After modelling data on nitrogen levels measured at sea with satellite images, they determined that organic matter coming from coastal areas was responsible for more than 90% of the nitrogen entering the wider Gulf. Large circular currents, or eddies, transport this organic matter out into the wider Gulf, an area of ocean that is normally nutrient poor—an open ocean desert. The circulating nutrients therefore have a major impact on the productivity of this area. The Gulf of Mexico is an important spawning ground for many species, including Atlantic bluefin tuna and mahi-mahi, and the nitrogen transported by the eddies is an important nutrient for the phytoplankton that form the foundation for the Gulf of Mexico food web, as well as these important fisheries target species.

Paper: https://www.nature.com/articles/s41467-021-23678-9

Grant: OCE-1851347; OCE-1851558

Caribbean coral reefs have been warming for longer than previously thought

The impacts of climate change on corals are an issue of major concern, To investigate the history of warming in the Caribbean, NSF-supported researchers from the University of North Carolina at Chapel Hill used satellite images and sea-surface temperatures collected in the field, from 5,326 Caribbean coral reefs, to look at warming trends from 1871 to 2020.

Throughout the Caribbean, coral reefs generally started to get warmer from 1915; however, in some locations warming began during the second half of the 19th century, soon after the industrial revolution began. Caribbean coral reefs have warmed by an average of 0.5 to 1°C in the past century, and if climate change trends continue, reef temperatures will have increased by 1.5°C by the year 2100. In addition, heat waves in

Credit: Colleen Bove

the Caribbean increased from an average of one per year in the 1980s to 5 per year currently. The researchers expressed their concern, stating that in addition to reductions in greenhouse gases, the removal of other threats to coral reefs, such as pollution and destructive fishing practices, is urgently needed.

Paper: https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000002

Grant: OCE-1737071

Credit: Andreas Teske

Hydrothemal vent crustaceans have a unique microbial ecosystem of their own

Hydrothermal vents are unique deep ocean ecosystems, often with animals and ecologies not observed anywhere else on the planet. In these locations, super-heated, mineral-rich water, which can reach temperatures of more than 300°C, flows into the deep ocean, where temperatures are at a chilly 3°C.

NSF-funded researchers from the University of Oldenburg investigated a species of white, deep-water squat lobsters inhabiting hydrothermal vents in the Gulf of California. They found that these lobsters host a unique microbial ecosystem, very different from their surroundings. Squat lobsters were collected from a depth of 2km with the help of the NSF-funded submersible *Alvin.* Amongst the microbes coating the lobsters, various methane and sulfide-oxidizing bacteria were found. In a region where energy-providing sunlight is totally absent, these microbes can turn chemicals such as hydrogen sulfide and methane, which flow from the vents, into energy. The squat lobsters may use the bacteria living on their shells as a source of nutrients. However, the bacteria may also help to detoxify poisonous hydrogen sulfide on the lobsters' bodies—the next step for the researchers is to try to identify the benefits that the lobsters gain from their microbial coatings.

Paper: https://www.nature.com/articles/s41598-022-06666-x

Grant: OCE-1357238

Credit: Chris Parsons, NSF

Looking to the climate past to determine our climate future

The last time Earth saw atmospheric carbon dioxide concentrations over 400 parts per million (ppm) was in the Pliocene, over 3 million years ago. We are currently at about 420 parts per million in summer months and rapidly increasing—we were at ~405 ppm just 5 years ago. The Pliocene climate was warmer, however, than the present day, by 2–3°C. In addition, the Pliocene looked very different from the current day—for example, dry desert areas, such as the Sahel in Africa and Northern China, were much wetter and greener in the Pliocene. NSF-funded researchers at the University of Connecticut have been using climate models to find out more about the climate in this epoch, when greenhouse gas levels were high, in order to gain clues as to what our own climate future might look like.

One of the unexpected effects they found was that warming, the reduction of ice sheets, and an increase of vegetation led to a lowering of surface albedo—the ability of Earth's surface to reflect sunlight back into space. This had a major impact on the hydrological cycle, allowing for greater evaporation and changing patterns of moisture transport. These findings raise concerns—certain locations are already receiving high levels of summer rainfall, including Southeastern Asia, Northern India, and West Africa, and they may see even more rainfall and increasing flooding soon.

Paper: https://www.nature.com/articles/s41467-022-28814-7

Grants: OCE-1903148; OCE-1903650; OCE-2103015 changes worldwide. In addition to warming, ocean waters are becoming more acidic and sea levels are rising. Extreme weather events are increasing in severity and frequency as climate change progresses, often damaging some of our most vulnerable communities. NSF supports researchers who are studying these extreme events so that we can better predict and minimize their impacts.

Climate change and nutrient pollution are promoting more frequent and severe harmful algal blooms, threatening our coasts and Great Lakes. This threat is gaining recognition; for example, there is an interagency working group currently putting together a report for Congress on harmful algal blooms in the Great Lakes, which should come out later this year.

Climate change threatens human societies and cultures. Therefore, multidisciplinary approaches are vital to integrating our understanding of the intersections of climate change, oceans, and people. NSF is meeting this challenge by developing innovative new programs, such as the Coastlines and People Program or CoPe. CoPe supports diverse, innovative, multi-institution awards, with projects involving local stakeholders and incorporating diverse perspectives to holistically tackle the impacts of climate change on coastal communities.

These are just a few examples of where NSF is working to tackle the impacts of climate change, on the oceans, on ecosystems, and on human communities.

Solutions

For our blue planet, the ocean must be part of the climate conversation. Oceans fit into the climate solution space in many ways; for example, offshore wind is key to increasing our immediate large-scale capacity for clean energy and attain our Nation's pledges for reducing carbon dioxide emissions. But reducing emissions will only help to slow the increase in global temperatures. By restoring marine ecosystems like mangroves and seagrass beds, the ocean can also help sequester "blue" carbon. Moreover, the National Academies recently released a report on Marine Carbon Dioxide Removal (mCDR), which has the potential to help repair our damaged climate systems.

NSF is a vital part of the research-to-action pipeline. We do foundational work, providing information and tools, that enables other agencies and bodies to accomplish their ocean and climate-related goals.

For example, NSF data are always publicly accessible and free, available to decision-makers, resource managers, and coastal communities. NSF research also advances technological development, contributing essential tools that can be applied toward ocean-based climate solutions. These solutions are a national and global focus right now. NSF is a co-chair of the White House Subcommittee on Ocean Science and Technology (SOST). SOST recently released a report entitled *Opportunities and Actions for Ocean Science and Technology (2022-2028)* to enable agencies to better incorporate Federal ocean science and technology priorities into decision-making and implementation. This report identifies goals and opportunities related to using ocean science and technology to combat climate change (bit.ly/3KUbm43).

Globally, the United Nations Decade of Ocean Science for Sustainable Development (aka the Ocean Decade), which started last year and runs through 2030, calls on the international community to unlock innovative ocean science solutions to foster an equitable and sustainable world. Engaging in the Ocean Decade is one of the opportunities identified in the SOST Opportunities and Actions Report. The Ocean Decade is also a perfect example of how NSF's work can further the goals of other agencies. For example, one of the official UN-endorsed Ocean Decade Actions is the NSF-funded Global Ocean Biogeochemistry Array (GO-BGC). This global network of ocean-analyzing floats will be used to collect essential data to help identify environmental changes and to provide decision-makers with the science they need to better, and more sustainably, manage ocean resources.

Comprehensive knowledge about our oceans is integral to understanding the potential they hold for mitigating climate change. NSF's partnerships and involvement in efforts such as the Ocean Decade allow us to further our important role in developing ocean climate solutions. We value this collaboration because it allows us to be part of this global movement, as we recognize there is just one global ocean, and we are all both connected to, and reliant upon, it.

Stay safe and healthy,

Terry Quinn

Director, Division of Ocean Sciences