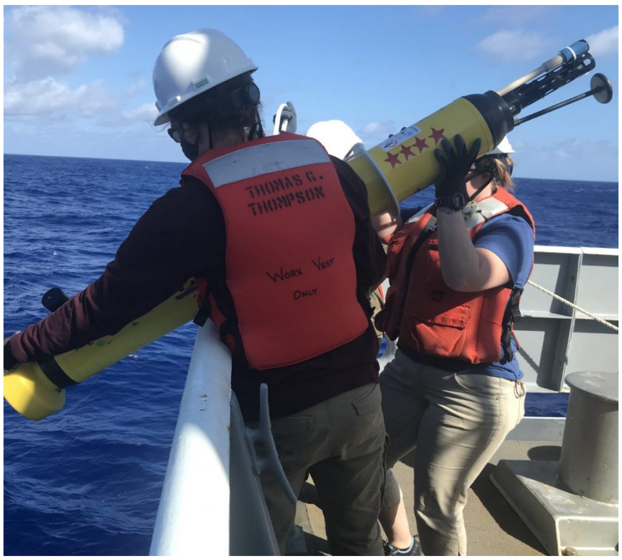
Fleet of robotic sensor floats provides important data on carbon uptake by ocean phytoplankton



Credit: Andreas Thurnherr

Primary production in the oceans (the uptake of carbon dioxide and its incorporation into organic molecules via photosynthesis) reduces atmospheric carbon dioxide by 200 parts per million (approximately half of the current level of atmospheric carbon). Therefore, understanding the uptake of carbon dioxide, its conversion, and then storage in the ocean (a process called the “carbon pump”) is very important in the study of climate change.

The estimate for the amount of primary productivity has previously involved satellite images measuring phytoplankton levels and then using ship-based surveys over a relatively small area to calibrate these satellite images. However, the Global Ocean BioGeoChemical Argo Array (GO-BGC) has allowed this measurement over large areas of ocean, including areas where few research surveys have occurred, such as the Indian and Southern Oceans. The GO-BGC consists of hundreds of robotic floats that measure temperature, salinity, oxygen, pH, chlorophyll, and nutrient levels. When deployed in the ocean, the floats sink to a depth of a kilometer and then drift at this depth. Every 10 days they sink to a depth of 2km, then ascend to the surface, collecting data as they go. When they reach the surface, the floats beam their data to a satellite – these data can then be downloaded by scientists in their labs.

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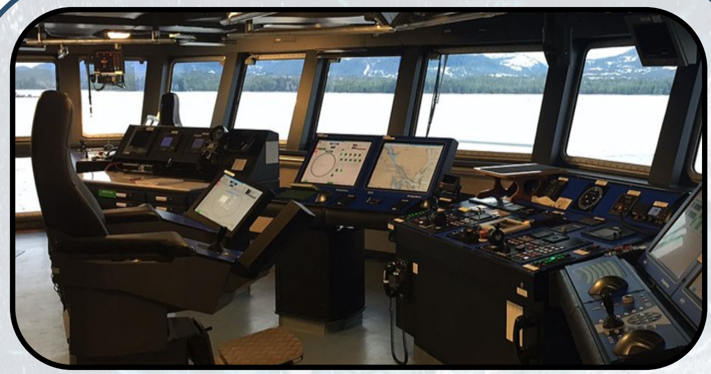

A view from the bridge

The Division of Ocean Sciences recently held the 3rd Annual Frontiers of Ocean Sciences Symposium (to see a video of the meeting please visit: https://www.nsf.gov/geo/oce/ocean-frontiers/Frontiers-video_final-july2021.mp4).

The symposium had four early career scientists from universities across the country share their research and their thoughts about the future of the ocean. We also had a panel of speakers from last year’s meeting, discussing the symposium’s theme: *the future of the oceans*. We discussed the following questions: What will the oceans of the future look like? What will the *ocean science* of the future look like? But most importantly, *who will be* the ocean scientists of the future?

This latter question is very important to me. I would like to see a diverse and inclusive field of ocean scientists that truly reflects the diversity of this nation, where anyone who has an interest in ocean science has the opportunity to access the classes and resources that they need to study in this field.

But, before we talk about the future, perhaps we should look back to the past and see how ocean science and ocean scientists have changed during the history of the National Science Foundation, and even during my career.

The National Science Foundation was established in May 1950. Four of NSF’s first 100 awards were related to ocean science, so NSF has been a leader in basic ocean science since its establishment. But it was a very different world back then. In many parts of the US, schools, restaurants, and public transport were segregated. Oil was just starting to take over from coal as the world’s foremost energy source. Fish were seen as an inexhaustible resource in the oceans and

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there was an active whaling industry in the Antarctic. The US had just come out of the second world war, and many in ocean science learned their trade in the military. With a few notable exceptions, ocean scientists were almost exclusively white males. In addition, a great deal of ocean science data and information we now take for granted were considered to be a closely guarded state secret. Moreover, the closest thing to a personal computer was 4 cubic feet in size and had just two bits of memory (or one 4 millionths of a megabyte).

In the 1950s, in my field of marine geosciences, some of the basic concepts of the field, like plate tectonics, seafloor spreading, and continental drift, were considered to be controversial ideas. Indeed, the ground-breaking marine geologist and underwater cartographer Marie Tharp's revolutionary ideas on seafloor spreading were infamously dismissed as "girl talk". Marie Tharp herself wasn't even allowed to go on an oceanographic expedition until 1965, when she went on the NSF research vessel *Eastward*, which was the only ship allowing female scientists onboard.

However, over the past 70 years not only have the state of the oceans changed dramatically, but the nature of ocean science and ocean scientists has likewise changed drastically. Even in my lifetime, how ocean science is conducted has changed tremendously. When I was starting my PhD, a cutting-edge home computer had just 64 kilobytes of memory. The National Science Foundation Net had just been proposed – a then innovative idea about having a network of computers to share scientific and educational information. The internet did not exist. There was no such thing as email. Mobile phones, if you could afford one, weighed over 2 pounds, took ten hours to charge and ran out of power in just 30 minutes. But, some of the first ocean observation systems were also being deployed in the mid-80s, to measure ocean temperatures as scientists were starting to become concerned about the changes in global climate.

Thirty-five years later, just as the iPhones in our pockets are the descendants of the Commodore 64 computer and 2-pound mobile phones, the recently funded Global Ocean BioGeoChemistry Array (GO-BGC) descends from these early ocean observation systems. This new system will transform the way we observe the global ocean, deploying 500 floating robots around the world, collecting important biological, chemical, and physical data from the ocean surface to 2km deep. This system will provide essential data on how climate change is changing the ocean's chemistry, biology, physics, and geology.

When I was a PhD student, the idea of having a fleet of robotic floats automatically collecting ocean chemistry and geological data throughout the water column, and then beaming those data wirelessly to a home computer so they could be analyzed, was science fiction. Work then would have required labs full of scientists, each with their own most decidedly

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Remote and local drivers of Pleistocene South Asian summer monsoon precipitation: A test for future predictions

In a recently published study by NSF-funded researchers, Steve Clemens and colleagues reconstructed the South Asian summer monsoons during the Pleistocene, a time period characterized by natural fluctuations in global carbon dioxide and ice sheet volumes. Their goal was to determine the effects of higher atmospheric CO_2 levels, greater moisture, and rapid ice melting on the South Asian Summer monsoons' precipitation and Indian subcontinental runoff. Pleistocene monsoon reconstructions, the researchers believed, could help model monsoon events in a warmer future climate. During a two-month cruise in the Bay of Bengal, the researchers collected sediment cores, drilled by the Integrated Ocean Discovery Program, offshore of the Mahanadi River Delta on the Indian continental shelf. The drilled sample cores, some slightly more than 200 meters in length, allowed the researchers to incorporate multiple factors, or climate proxies, in their paleoclimate reconstructions.

The researchers' results showed that over the past million years, increases in atmospheric CO_2 levels were followed by increases in precipitation, a pattern that may also occur in response to current anthropogenic increases in greenhouse gas concentrations. Their models predict South Asian Summer monsoons having more intense and variable rainfall and precipitation, as well as an increasing run-off of surface water resulting from this precipitation.

Studying Pleistocene climate change is crucial to understanding how higher greenhouse gas levels may affect future monsoon seasons. In South Asia, where monsoonal rain is essential for agriculture and day to day living, being able to accurately make predictions about monsoon seasons has large implications for a region where nearly 1/5 of the world's population lives. As greenhouse gases increase in the atmosphere, it is predicted that overall monsoon precipitation and the prevalence of extreme monsoon events will increase too. Similar methods can be used to study other regions where hurricanes are increasing in intensity, and the data can be used to help populations in these areas better prepare for the forthcoming impacts of climate change.

Paper: https://advances.sciencemag.org/content/7/23/eabg3848

Grant: OCE-1634774

NSF Infrastructure: JOIDES Resolution

Could wetlands be the solution to rising sea levels?

Climate change and rising sea levels are arguably the challenge of our lifetime. The conversation has shifted from what climate change is to how we can survive the impacts that will result from higher temperatures and higher sea levels. Sea levels are expected to rise by 10-25 millimeters per year by 2050. NSF-funded scientist Matt Kirwan believes that wetlands may help us fight rising sea levels. He argues that wetlands adapt when sea levels rise and simply move inland alongside rising sea levels. This is significant, as wetlands hold large amounts of carbon and as a result are essential for carbon storage. Their destruction releases immense amounts of stored carbon. They also serve as storm protection for any coast in which they exist, helping communities affected by an increased frequency of natural disasters.

The process by which wetlands adapt to higher sea levels is a biophysical feedback loop. Wetlands slow incoming salt water and absorb the sediment the water carries. As a result, soil surface increases and wetlands are raised, protecting them from drowning. This research has been conducted over the last 20 years in various locations around the US and Canada. The most recent study was conducted along the Severn River in southern Virginia. Researchers used peat corers to reveal mineral soil, showing that the wetlands were recently created. These cores helped show that wetlands can adapt to rising sea levels and expand vertically or horizontally if there are no physical impediments such as a cliff or manmade impediments such as roads or levees. These results are encouraging, but also highly debated within the scientific community. Many scientists believe that sea levels will rise too quickly for wetlands to adapt. For example, the studies of NSF-funded researcher Torbjörn Törnqvist suggests that wetlands are particularly susceptible to sea level rise and may not be able to adapt. Scientific evidence currently exists for both conclusions, but the race is on to conduct studies to test whether wetlands will be able to withstand climate change impacts or not.

Papers: https://www.sciencemag.org/news/2021/06/ecologist-thinks-coastal-wetlands-can-outrun-rising-seas-not-everyone-s-convinced
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000334

Could whale calls be used for seabed exploration?

Fin whales are the second largest of the whale species, and also produce some of the loudest calls in the animal kingdom. These loud, extremely low frequency calls can travel great distances in the ocean (20Hz; 189 dB re 1μPa) but NSF-funded scientists recently found that these calls can also penetrate the seabed and bounce off sub-seabed structures. Václav Kuna and John Nábělek were monitoring seismic data from seabed monitors at a depth of approximately 3km. They found that they frequently recorded fin whale calls, being produced by animals from distances of up to 19km away.

In addition to the whale calls, they found that the sounds were passing through the seabed sediment to depths of over 500m and echoing off geological structures below. Exploration for oil and gas also uses sound produced by "airguns" (compressed air explosions) to echo off sub-seabed geological structures during "seismic surveys," but because of the high sound levels and impulsive nature of the sound involved, there is concern about the impacts of seismic surveys on whales and dolphins. The researchers suggested that the calls of fin and other species of whales could potentially be used in lieu of seismic surveys, in some areas, to gather information on what lies below the seabed, stating that "our study demonstrates that animal vocalizations are useful not only for studying the animals themselves but also for investigating the environment they inhabit."

Paper: https://science.sciencemag.org/content/371/6530/731

Grants: OCE-1031858; OCE-1131767

Photo Credit: Chris Parsons

Ocean drilling reveals the history of impacts along the Yucatán coast

The Chicxulub crater off the Yucatán coast of Mexico is believed to be the crater created by the asteroid that led to the extinction of the dinosaurs about 66 million years ago. When the asteroid hit, the impact sent a cloud of the rare element iridium up into the atmosphere, which then spread around the globe and settled in a layer of microscopic particles around the Earth. In 2016, drill cores in the crater discovered a layer of iridium, confirming the connection between this crater and the asteroid impact, as well as the 66 million-year-old layer of iridium around the world.

When the asteroid hit the Earth's surface, the latter behaved like a liquid — imagine dropping a stone into a bowl of water that quickly freezes. The impact created a crater that was more than 12 miles deep, piercing the Earth's mantle, and forcing rock from the mantle up to the surface, forming a ring of mountains surrounding the crater, like ripples. Also in 2016, scientists extracted an 835m drill core from the crater and analyzed the age of surrounding mountain peak granite. The granite in these mountain rings was estimated to be 334 million years old. What scientists found in the drill sample was surprising and led them to discover that the rocks within the crater were very different to the rock of the crater itself.

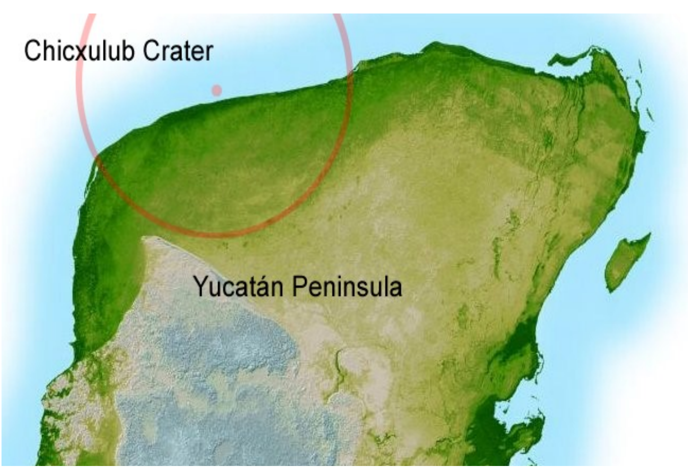


Photo Credit: NASA

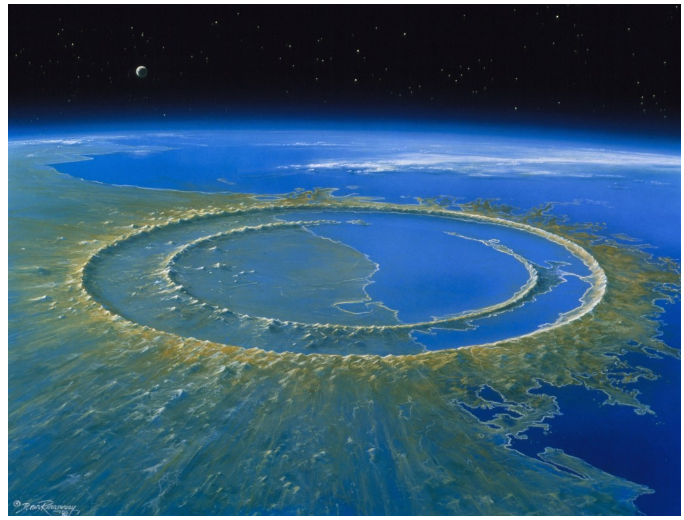


Photo Credit: Science photo library

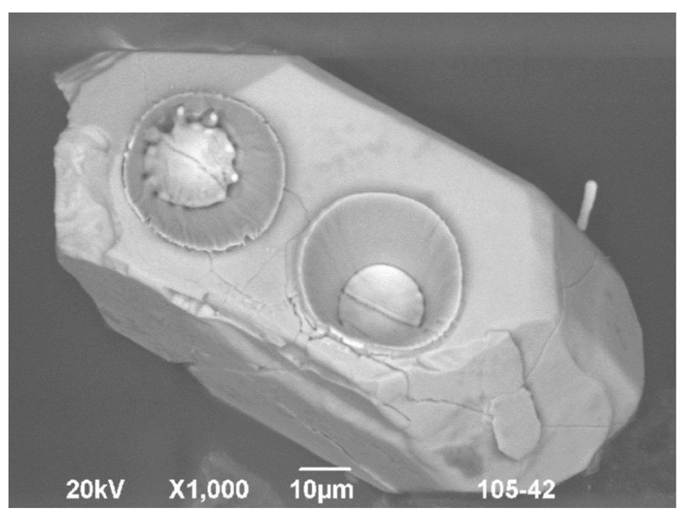
Scientists analyzed crystals of zircon, which can act like tiny "clocks" in rock, helping to study geological history. They found three much older rock populations when analyzing the cores from the crater (400−435, 500−635 and 940−1400 million years old). These three different rock types had been brought to the surface from multiple subducted layers of the Earth crust underlying the impact location.

Like a decorator cutting through layers of carpeting and linoleum to find hardwood floors hidden beneath, the impact of the asteroid had brought rock to the surface from multiple layers of the Earth's crust, giving us a rare glimpse of the complicated geological history that had formed this part of the Mexican coast.

Papers: https://advances.sciencemag.org/content/7/9/eabe3647

https://pubs.geoscienceworld.org/gsa/gsabulletin/article-abstract/doi/10.1130/B35831.1/596574/Evidence-of-Carboniferous-arc-magmatism-preserved?redirectedFrom=fulltext

Grants: OCE-1736826; OCE-1736951; OCE-1737087; OCE-1737155; OCE-1737199; OCE-1737351



Zircon crystal

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 during the COVID-19 pandemic in 2020. In fact, the amount of sound energy in the frequencies produced by shipping was about two-thirds of what it averaged during the five years before the pandemic. The underwater noise data recorded from the Regional Cabled Array network is part of the Ocean Observatories Initiative (or OOI). In the second quarter of 2020, it was found that the number of ships entering Puget Sound decreased by 19% and the amount of shipping containers decreased by 17%, so the reduction in ocean noise aligns with a decrease 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 noise produced by large shipping vessels and thus may be acoustically affected by high levels of shipping noise.

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

Grant: OCE-1743430

Photo Credit: Chris Parsons

During the last historical warmest period, sea levels were not as high as previously thought

To try to predict what a warmer future on Earth will look like, many scientists look to the past, to the last interglacial period (the Eemian period, 130,000-115,000 years ago), when global temperatures were 1 to 2° C (1.8 to 3° F) warmer than during the current epoch (the Holocene). This was a period when sea levels were higher than today; looking to the height of the oceans then may help us to predict what coasts may look like in the future. However, making such predictions can be difficult, especially as the Earth's surface changes considerably more than most realize. People tend to think of the Earth's surface as being solid; however, it is more like a baked Alaska – a thin crust over a softer, viscous layer that is "squishier."

Photo Credit: Chris Parsons

In between warm periods, like the Eemian period and the present, ice ages occur where heavy ice sheets cover the Earth's surface. The weight of this ice causes depressions in some parts of the Earth's crust and forms bulges in other areas not covered in ice. As the ice melts the Earth's surface rebounds somewhat, as the weight of the ice is removed. Taking into account these movements is very important when trying to calculate historical sea levels, as some coastal areas may have been higher, or lower, than presently because of these processes. NSF-funded scientists found that historical predictions of sea level rise were different by up to tens of meters, in areas that eventually became covered by ice sheets, when the "squishiness" of the Earth's surface was taken into account.

Using data on the deformation of the Earth's crust and interior, researchers Blake Dyer, Jacqueline Austermann, and colleagues took historic sea level data from across the Bahamian archipelago to calculate the average global sea level rise in the Eemian. They estimated that although there was a 1 in 20 chance it could have been as much as 5.3m higher than sea levels today, it was most likely around 4m higher than current sea levels. This is slightly lower than previously estimated. From this they suggest that polar ice sheets may not have melted quite as much as previously thought.

This more accurate historical data in turn helps us to make more accurate predictions of what sea level rises in a post-global warming world could look like.

Papers: https://www.pnas.org/cgi/doi/10.1073/pnas.2026839118; https://doi.org/10.1093/gji/ggab289

Grants: OCE-1202632; OCE-1841888; EAR-2002352

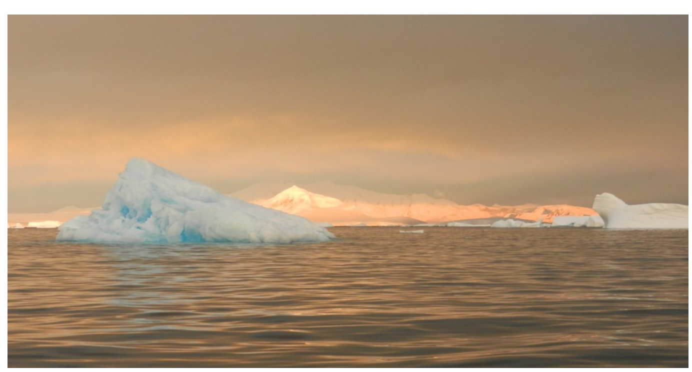


Photo Credit: Chris Parsons

Coral in the northern Red Sea display an encouraging resilience to high ocean temperatures

Coral reefs are in decline worldwide, partly because ocean temperatures are increasing, which leads to mass coral bleaching (when stressed corals expel their symbiotic algae or zooxanthellae) and mortality. However, a recent study funded by the NSF offers a glimmer of hope that some corals may be more resilient to high temperatures. Researchers found that, despite local water temperature rising faster than the global average, corals in the Gulf of Aqaba and the northern Red Sea did not show signs of bleaching. The researchers looked at patterns of gene expression in the common coral *Stylophora pistillata*, as well as its symbiotic algae. The ability of an organism to rapidly mount a gene expression response when exposed to heat stress, and bring the majority of these genes back to normal levels after the heat stress is removed, is referred to as "transcriptomic resilience." In this current study, when temperatures of up to 32°C were recorded (which is 5°C above the average monthly temperature), there was rapid expression of genes related to a heat stress response, but when the temperatures declined gene expression rapidly went back to normal in most of the coral. This suggests that the coral is resilient to some increase in temperature.

However, if the temperature increased to 34.5°C, there was minimal recovery and there was a high level of coral mortality, suggesting that this was the lethal temperature threshold. In addition, the coral's microbial communities became dominated by opportunistic bacteria species — like an immune-compromised patient contracting pneumonia in a hospital.

Although the northern Red Sea is already very warm, temperatures of up to 32°C are not predicted to occur in this area for the rest of this century at least. Therefore, according to the researchers, this gives "real hope for the preservation of at least one major coral reef ecosystem for future generations."

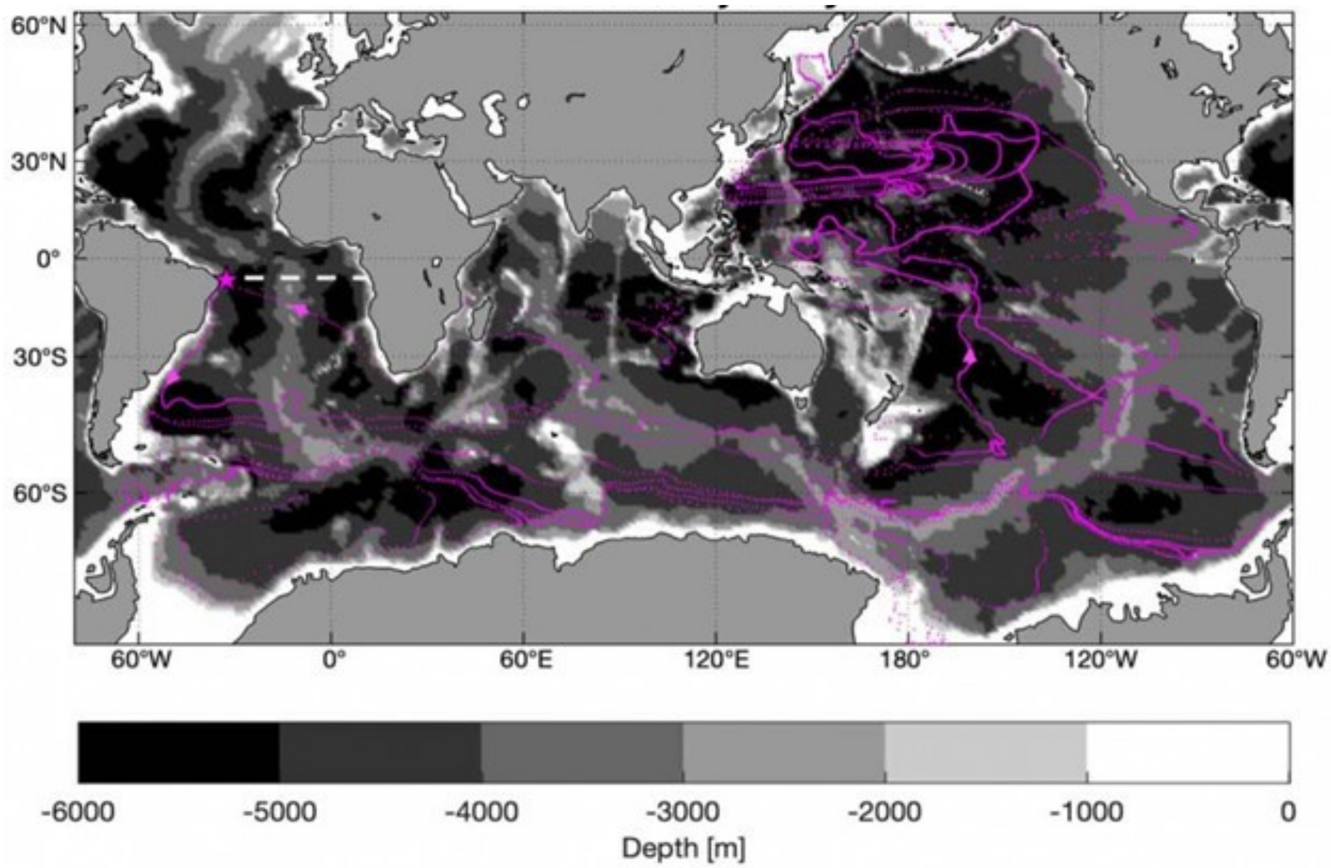
Paper: https://www.pnas.org/content/118/19/e2023298118?fbclid=IwAR3MGOMKhHKQZo380J-66_g34NOcQFLXBhVtS6CqkONHHgbKTzhr94EeJzo

Grants: OCE-1833201; US-Israeli BSF-2016403

Study on the circulation of Atlantic Ocean waters shows carbon will be stored in the deep ocean half as long as previously thought

Researchers at Scripps Institution of Oceanography and the Massachusetts Institute of Technology have estimated the time that it takes for water in different parts of the Atlantic Ocean to circulate around the world: from 300 to 2,800 years. The water taking the latter route (about half the amount tracked) was described as taking a "grand tour" of every ocean, including a thousand-year journey through the abyssal zone of the Pacific. The scientists used the Estimating the Circulation and Climate of the Ocean - or "ECCO" - model to come to this conclusion. The model took more than one billion data points collected over 25 years from satellites and robotic floats from the Argo network. The researchers simulated the movement of parcels of water originating in the lower branch of the Atlantic Meridional Overturning Circulation (AMOC), a large system of ocean currents that carries warm water from the tropics into the North Atlantic. As warm water flows northwards it cools and some evaporation occurs, which increases the salinity of this water body. Low temperature and increasing salinity make the water body denser and heavier, which

Credit: Scripps Institute of Oceanography



Seawater taking a "grand tour" of the world oceans

then sinks deep into the ocean. This cold, dense water slowly spreads southwards, several kilometers below the surface. Eventually, it gets pulled back to the surface and warms again, completing the circulation pattern. The movement of this water body, and the heat it transfers into the atmosphere, helps to moderate and stabilize atmospheric temperatures in the North Atlantic. The sinking water also takes carbon with it into the deep ocean, where scientists had assumed it would be stored for a long period of time until it eventually upwelled and was brought to the surface again. However, the study also concluded that atmospheric carbon was being kept locked in deep ocean waters for a shorter time than previously thought – in fact, half as long. This finding, that carbon could be released back into the atmosphere far more quickly than assumed, has major implications for longer-term climate change predictions.

Also, the researchers determined that an essential component of the Atlantic's circulation could be more vulnerable to disruption than previously thought. Increasing inputs of freshwater (e.g., due to melting ice) could destabilize the AMOC, which has major implications for extreme weather changes around the Atlantic and, indeed, globally.

Paper: https://advances.sciencemag.org/content/7/21/eabf5478

Grants: OCE-1634128; ACI-1548562

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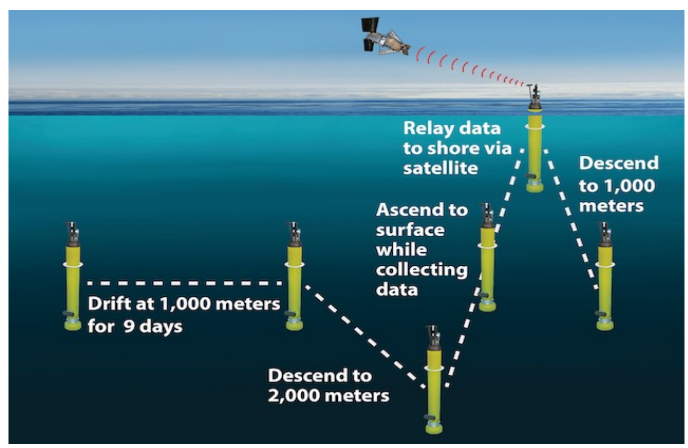

Credit: Kim Fulton-Bennett., MBARI

How a GO-BGC float collects data

The data gathered by these floats allowed NSF-funded scientists Ken Johnson and Mariana Bif to calculate how much carbon phytoplankton managed to produce via photosynthesis every year – 53 pentagrams (or 53 giga tonnes or 53,000,000 million kilograms). The weight of this carbon is roughly equivalent to 200 million elephants. The data gathered by the GO-BGC floats will allow scientists to better predict how marine primary productivity will respond to changes in the ocean, such as warming temperatures, ocean acidification, changing levels of nutrients, and shifts in phytoplankton growth.

Paper: https://www.nature.com/articles/s41561-021-00807-z

Grants: OCE-1946578; PLR-1425989; OPP-1936222

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NOT portable computers.

What will it be like collecting ocean science data 35 years from now in a marine environment substantially altered by climate change and other anthropogenic activities?

To deal with the imminent and substantial challenges in the ocean environment, we need an innovative, multi-disciplinary, diverse, collaborative, and dynamic funding talent pool within the ocean sciences generally. Diverse backgrounds, perspectives, skills, talents, and world views lead to diverse ideas and solutions. Here at NSF, we strive to cultivate an education and research ecosystem that is inclusive and collaborative. The ocean science enterprise is strongest when we prepare a diverse, globally engaged STEM workforce.

To do this, we are expanding efforts to broaden participation from underrepresented groups and diverse institutions across all geographical regions in NSF activities. For example, NSF INCLUDES (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science) is a national program aimed at catalyzing the STEM enterprise to embrace diversity so that the STEM workforce reflects the diversity of the nation. In the ocean sciences, the NSF STEM Student Experiences Aboard Ships – or STEMSEAS – program is a 3-year partnership between the Indiana University of Pennsylvania, Lamont Doherty Earth Observatory at Columbia University, and the University National Oceanographic Laboratory System, or UNOLS. It strives for 3 goals: (i) increasing the number and diversity of students pursuing degrees and careers in geosciences; (ii) preparing students for all possible career trajectories in the geosciences, and (iii) con tributing to the evidence base for effective student engagement, learning, and retention in STEM.

With the Consortium of Ocean Leadership, NSF has funded workshops to discuss the attrition of women in the academic ocean sciences leadership pipeline. Other workshops have discussed policies and best practices to address sexual harassment in ocean science field research and how to reach new demographics, such as rural communities, through informal ocean science education.

Programs like these are making great progress on broadening participation, but we must stay vigilant and do more to ensure every student and researcher is included and reaches their greatest potential. We must continue to improve the overall safety, inclusivity, and productivity of research settings to attract, empower, and retain the best and brightest.

But there are challenges we urgently need to address. As a recent and dramatic example, the pandemic did not affect all scientists equally. Early career and female scientists were particularly hard hit, as were scientists in minority-serving institutions, especially tribal colleges and historically Black colleges and universities. NSF has made efforts to support our scientists through these difficult times.

As the pandemic recedes, we also need to look at the lessons that we have learned regarding assisting the hardest hit demographics. Questions to ask ourselves include:

How can we better support scientists who have young children, or who are care-givers?

How can we better level the playing field for scientists and students with physical or learning disabilities?

How can we aid scientists and students who are not born to privilege so that they are not penalized or prevented from achieving their full potential?

How can we ensure equality for scientists and STEM students regardless of their gender, race, upbringing, family status, culture, sexual orientation, age, or geographical location?

In a time of grave ocean challenges and ocean science needs, but also a time of increased competitiveness for science positions and funding, how can we ensure that the students and early career scientists of today can have long and meaningful careers where their talents can be fully utilized and their ideas come to fruition?

To help early career scientists, I'm pleased to announce that the Division of Ocean Sciences has recently launched a new post-doctoral fellowship. These fellowships provide opportunities for scientists early in their careers to work within and across traditional disciplinary lines, develop partnerships, and avail themselves of unique research resources, sites, and facilities. The fellowship program is intended to provide beginning investigators of significant potential with experiences that will establish them in positions of leadership in the scientific community. The Fellows will include participation in a professional development program that emphasizes development of mentoring skills and that coordinates the involvement of Fellows in conferences and activities that are focused on increasing the engagement of underrepresented groups in STEM. Applicants who are women, veterans, persons with disabilities, and underrepresented minorities in STEM, or who have attended community colleges and minority-serving institutions, are especially encouraged to apply.

I hope that this will be one of many new, additional initiatives that we can announce to help the ocean scientists of the future gain the essential experiences and opportunities they need to start long and productive careers.

Stay safe and healthy,

Terry Quinn

Director, Division of Ocean Sciences