Listening to the Ocean Offers Insights into Climate Change

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Introduction

Oceanography classes teach that sound is to the sea what electromagnetic radiation, or light, is to the atmosphere. And, in fact, oceanographers and acousticians study the ocean environment using sound with a goal of understanding how new sources of sound may travel through the many layers of seawater that make up the ocean. To do this, they interpret noises of the environment that are picked up by hydrophones.

Indeed, acoustics offers a window into the undersea realm. The ocean's acoustic environment, also known as the ocean soundscape, incorporates sounds, or "signals," from humans, animals, plants, weather, the seafloor, and surface waves. Moreover, how ocean animals perceive and respond to these signals tells us a lot about the undersea environment. On short timescales, animals may change their behaviors to be quieter to avoid predators or to vocalize at the same time, cued by a full moon, to attract mates. On longer timescales of years, patterns in whale song or fish calls shift in response to the environment changing, in terms of both human use and climate change.

We know that many ocean environments are in a state of stress and flux due to ocean warming, ocean acidification, shifting weather patterns, and other effects of climate change (Garcia-Soto et al., 2021). Marine species have adapted to the historic specific ranges of temperature, salinity, and pH (e.g., Sanford, 2014; Costello et al., 2017). But now, these variables are no longer following their historic norms due to an excess of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere and ocean, and this has a potential impact on marine species. This can be a major problem for certain species, which can have cascading effects on ocean ecosystems. One way to understand and monitor what is happening in the maritime environment under this extreme stress is through the use of acoustics. In fact, acoustics may also inform human efforts at ecosystem conservation, mariculture, and carbon capture. Indeed, numerous studies on ocean soundscapes incorporate data from coral reefs to a wider range of environments including temperate reefs (Van Hoeck et al., 2020), kelp forests (Gottesman et al., 2020; Butler et al., 2021), deep reefs (Archer et al., 2018), and pelagic environments. This article focuses on the intersection of ocean soundscapes and climate change.

Ocean Soundscapes

The unique mixture of physical noise, biological noise, geologic noise, and anthropogenic noise in the sea comprise the soundscape (Cotter, 2008; International Organization for Standardization, 2017). Of importance, each marine ecosystem and environment has a unique soundscape that provides information about where one is in the world's oceans and estuaries, what the weather is above and below the surface, what plants and animals are passing through or are resident in that location, and how humans are utilizing that particular piece of the ocean. If we understand the soundscape, we understand the environment.

Soundscapes in the air are quantified relative to a human's perception of the acoustic environment, which incorporates sound sources and the ability of humans to detect these sources (Aletta et al., 2016). Soundscapes are often described in association with a place, such as a temperate forest in the spring, an aspen forest in Colorado in the fall, New York City's Fifth Avenue at rush hour, or an Irish pub in your town. Although none of those descriptions include any audio information or spectrograms, each description likely invoked ideas of particular sounds as you read them.

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Underwater, human perception of sound is less relevant than the sounds received at a hydrophone for humans to study later or the sounds received by ocean inhabitants. This is how underwater soundscapes are defined in a previous *Acoustics Today* article (Miksis-Olds et al., 2018) as "the sum of multiple sound sources that all arrive at the location of a receiving animal or acoustic recorder." The underwater soundscape will usually integrate sound sources over a much larger area than an in-air soundscape due to the nature of sound wave propagation through seawater. A hydrophone or marine animal could be receiving sound sources from thousands of kilometers away as well as from sources just a few meters away.

In underwater acoustics, the key distinction between ambient noise and underwater soundscapes is that ambient noise is all background noise that is not readily identifiable and soundscapes include all sounds in the environment (Cato, 2018). There is an ongoing discussion in the underwater acoustics community of incorporating perception by the listener into the definition of an underwater soundscape, particularly in the context of behavioral ecology and changes in species behavior under different soundscapes. Is perception simply the signal that can be received by a particular animal, which we calculate mathematically from both the ability of the sound source to travel through seawater to reach the auditory mechanism and physiologically from the nature of the auditory mechanism? Or do we go another step and include the response of marine animals to these auditory signals? The former is aligned with the in-air definition of a soundscape (Grinfeder et al., 2022, and references within). The latter focuses on the contribution of anthropogenic sound to marine environments, resulting in modification of behaviors of marine animals.

Soundscapes and Marine Life

Soundscape studies have revealed a wealth of information about ocean ecosystems. Fish calls and choruses continue to be discovered around the world, with many ocean ecosystems hosting a range of fish choruses, each with a different function (McWilliam et al., 2018). Individual fish calls tend to bedrums, purrs, and croaks ranging from 500 to 2,000 Hz. During spawning aggregations, fish vocalize in unison. In Golfo de Santa Clara, Mexico, for example, local fishermen have observed that the chorusing corvina (*Cilus gilberti*) are so loud underwater that they can be heard in air, quite the acoustic spectacle (Freeman, personal communication, 2013)! Along the mid-Atlantic Coast of the United States, the aptly named oyster toadfish (*Opsanus tau*) males call in a series of grunts and croaks called a "boatwhistle" to attract mates to its nest (Fine, 1978). Listen to an oyster toadfish call at bit.ly/Opsanus. On the other side of the world in the Indo-Pacific, frogfish (*Antennarius sp.,* commonly referred to as frogfish in the Northern hemisphere and anglerfish in Australia) have a similar ecological role (Myrberg, 1997). Both the oyster toadfish and frogfish look rather lumpy and odd (**Figure 1**), both are poisonous, and both vocalize loudly both to scare intruders away from their territory and to attract a mate. Indeed, fish calls are often associated with spawning or efforts to attract mates, with the oyster toadfish being just one particularly noisy example.

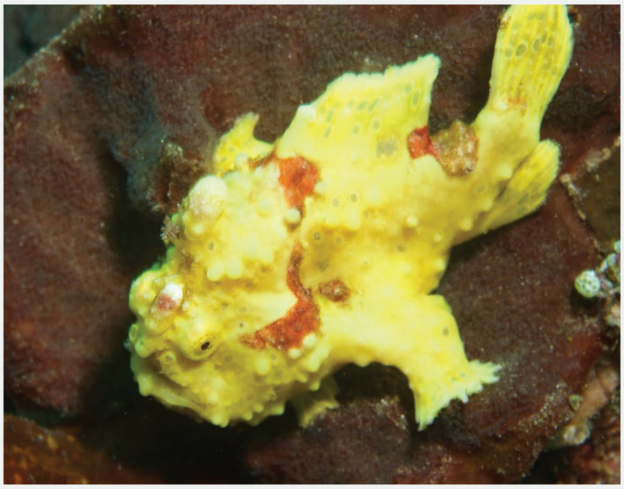

Figure 1. *The frogfish, like the toadfish (not shown), does not have a common fish shape nor does it swim well. Both are bottom dwellers that are poisonous snacks to their predators and discourage predation by vocalizing. In addition, the male fish of both species call loudly to encourage female mates to visit their nests. Photo by L. Freeman.*

The soundscape of a coral reef is akin to our own heartbeats, revealing the health and state of the ecosystem itself (Freeman and Freeman, 2016). A healthy reef has an acoustic signature that is rich in low-frequency sounds, including fish calls and invertebrate snaps, clicks, and pops (**Figure 2**). The Hawaiian damselfish (*Dascyllus albisella*) are small but incredibly noisy, acting like guard dogs barking at anything that gets too close to their nest. Many damselfishes in the family Pomacentridae are similarly noisy and

Figure 2. *A crab nestled inside live coral. This is a simple example but illustrates one of the primary sound production mechanisms by invertebrates on coral reefs. Invertebrates have hard shells or external skeletons. As they move about the hard surface of the coral reef, the shells hit the reef structure and click or snap, creating a portion of the background snap, click, and pop of invertebrate sound common to healthy coral reef soundscapes. Photo by L. Freeman.*

territorial in tropical and subtropical waters around the world. Listen to a dusky damselfish (*Stegastes fuscus*) call at bit.ly/DuskyDamsel. The damselfish calls are intermixed with the crunch and scrape of parrotfish biting algae off hard coral skeletons (**Audio file** at bit.ly/Freeman-Scrape1), the lower frequency purrs of groupers, the chatter of reef fish searching for food (**Figure 3**), and the ever-persistent snaps, clicks, and pops of hundreds of thousands of invertebrates within and atop the coral reef structure that forms the base of this ecosystem.

Soundscapes provide a fascinating way of monitoring and understanding ecosystems in single snapshots of time, but the story does not end there. The soundscape, or acoustic signature, of a healthy reef is so ingrained in the corals and fishes that make up the reef community that their larvae may use sound to help find an optimal place to settle out of their pelagic phase before "selecting" their final home (e.g., Gordon et al., 2018). Examples of sounds of a dying reef are available at bit.ly/dyingreef and of a healthy reef at bit.ly/Reefsound. These videos have striking visuals, but if you close your eyes, you could just as easily imagine being in a tropical rainforest, the terrestrial sister ecosystem to the ocean's coral reefs, two of the centers of biodiversity on planet Earth.

Healthy reef sounds attract greater numbers of certain types of reef fish larvae and coral larvae, as demonstrated

Figure 3. *A healthy coral reef. The reef scene from Indonesia with healthy coral and abundant fish shows the potential biodiversity and biomass in a coral reef ecosystem. Coral reefs are sometimes deemed the rainforests of the sea because they have so many species occupying the ecosystem. Such a rich ecosystem has an equally rich soundscape when in good health. Photo by L. Freeman.*

in a series of experiments and in situ observations (e.g., Boulais et al., 2024). Larvae spend several weeks in a planktonic phase adrift in the ocean. Once the planktonic larval stage is complete, the animals undergo further metamorphosis into a juvenile that resembles the adult. At that time, there are several environmental cues that the larvae use to determine an optimal place to end their planktonic phase by sinking to the ocean floor, hopefully on a coral reef, and take up residence for their adult lives.

One of those cues for coral reef fish and corals themselves is healthy reef sounds. However, although a number of scientists have shown that healthy reef sounds enhance larval recruitment, it is not yet clear exactly which component of healthy reef sounds is creating a cue for the larvae. Understanding how and where healthy reef sounds can be used to enhance restoration, coral farming, and conservation efforts is an exciting intersection of underwater soundscapes, coral reef ecology, and marine conservation. Furthermore, coral reef soundscapes are now well enough understood to not only track the current health status of a particular ecosystem but to also actually use the essential ocean variables of ocean sound as a means of identifying and tracking ecosystem recovery on restoration projects (Lamont et al., 2022).

Seagrass beds and marine algae also contribute to the soundscape (Freeman et al., 2018), though not in the same way that fishes vocalize or shrimps snap. Seagrass and algae emit sounds as a by-product of photosynthesis when the oxygen waste product is exuded from the plant along the surface and forms bubbles. As the bubbles grow, buoyancy forces exceed the surface tension (also known as the van der Waals force), physics forces drive the bubbles upward away from the plant, and the bubbles produce sound as they rise through the water column at a frequency proportional to their size. This ringing is at higher frequencies than typical reef sounds but is still audible to human hearing if played back from a hydrophone recording. The bubbles produce a series of short-duration transient sounds that are typically present in such large numbers that they give the impression of a lasting high-frequency ring.

Anthropogenic Climate Change

Underwater acousticians are continuing to discover just how critical soundscapes are to marine life, with a growing group of scientists contributing to the field. The nascent observation that healthy reef sounds improve larval recruitment is still being tested in new environments and with additional species. As we work to understand the intricate relationships between ocean ecosystems and acoustics, we are simultaneously documenting the changes in those ecosystems being driven by climate change. Understanding and mitigating these changes, which are caused by industrial enrichment of greenhouse gases in the Earth's atmosphere, is one of the grand challenges of our time. Humans have perturbed the Earth system such that the ocean environment itself is changing on a regional scale.

The impacts of anthropogenic climate change exacerbate a myriad of issues even well beyond the need of animals to use the sounds; these issues include things such as food security and national security. Humans have emitted 2.3 trillion tons of CO_2 since the Industrial Revolution on a timescale of hundreds of years, far more rapid than past geological climate oscillations. The plants and animals that comprise ocean ecosystems have honed their behaviors over millions of years of evolution, including their use of sound production and of their soundscape. Scientists are just beginning to understand the intricacies of some ocean soundscapes and how critical they are to the animals that reside in oceans, bays, and estuaries; at the same time, the ocean itself and likely the associated soundscapes are changing rapidly. Although nations are committing to reducing emissions now, significant effects have already changed the Earth climate system to include ocean warming, ocean acidification, reduced sea ice, increased storm frequency and severity, atmospheric rivers, and modified precipitation patterns (see the Intergovernmental Panel on Climate Change Sixth Assessment Synthesis Report at ipcc.ch/ar6-syr). Many of these weather and physical impacts are directly translated as underwater ambient sound sources, be it rainfall, wind, or changing sea ice dynamics.

Understanding how climate change is shifting ocean environments is paramount to providing effective tools for marine conservation and to developing and maintaining a scientific record of how the ocean and its inhabitants interact without the influence of human activities. Many of the physical and chemical shifts affecting the global oceans are not only well underway but are accelerating. For example, ocean surface warming from 2010 to 2019 has accelerated to 4.5 times the average per decade (Garcia-Soto et al., 2021). The ocean's decadal warming rate or temperature increase over 10 years from 2010 to 2019 is twice that of the previous decadal time period (2000–2009), and the circulation rates of the Atlantic Ocean are slowing down as well (Garcia-Soto et al., 2021).

Changing Seawater Properties and Acoustic Propagation

Understanding soundscapes is not only limited to tracking acoustic sources but also to the ability of signals to reach a particular receiver or the ability of sound to travel through seawater. Climate change will shift the acoustic properties of seawater, and thus the velocity of sound through a particular area of the ocean. Although temperature is a key driver of sound speed in water such that higher temperatures result in an increased sound speed, pH will have profound impacts, particularly at high latitudes, such that lower pH values are associated with higher sound speed. Ocean pH is regulated by the global carbon cycle and uptake of CO_2 in the ocean. The ocean and atmosphere seek equilibrium and as atmospheric CO_2 increases in the atmosphere, the ocean also absorbs additional CO_2. This additional CO_2 dissolved in seawater leads to a series of chemical reactions between the gas and seawater, which affects pH or ocean acidity in making the water more acidic. This is more pronounced at higher latitudes because colder water, such as Arctic and Antarctic regions, can absorb more CO_2. For example, in the Arctic, pH is expected to drop from approximately 8.1 to 7.9 in the next 30 years, resulting in an increase in sound propagation for frequencies up to 10 kHz, with the effect most pronounced at 900 Hz (Duda et al., 2021). The chemical and physical laws driving these interactions also apply to lakes and rivers, which are similarly undergoing significant environmental shifts with rapid increases in atmospheric CO_2.

Modeling sound speeds from temperature and salinity data in future climate scenarios reveals global changes with particularly dramatic shifts in high-latitude environments (**Figure 4**) (Affatati et al., 2022). It is important to note that this result does not consider the effects of ocean acidification on sound propagation (described by Duda et al., 2021). However, this fundamental shift in the ability to send and receive information acoustically will potentially have impacts on several marine mammal species that rely on sonic and ultrasonic acoustic communication for social dynamics, mating, navigation, and feeding. Such effects would be most likely at high latitudes, where animals may need to adjust their acoustic communication frequency, duration, or call style to account for changes in sound speed and different water layers that trap or reflect sound (ducting). The change in sound speed and sound propagation would likely be secondary effects to changes in ocean temperature limiting suitable ranges for marine mammal species and reduced ocean pH threatening a major prey source of krill that would not be able to form their exoskeletons and survive in the more acidic waters. Marine species will need to adjust their ranges to find niches of water space that have the temperature, pH, and prey that they require to survive. Data from the National Oceanographic and Atmospheric Administration and other long-term acoustic monitoring programs are tracking marine mammal species distributions and biogeographic ranges because range shift is expected in the coming decades of ocean warming. As soniferous animals relocate their habitat range, they are introducing sound sources to the soundscape of their new home and removing their acoustic signals from the waters that they have left behind.

Acoustic Thermometry of the Ocean

Perhaps the best-known example of the interplay between climate change and underwater acoustics is acoustic thermometry of the ocean (ATOC) as initially proposed by Munk (1993). In short, warmer water has a higher sound speed. If you consider a source and receiver from the same respective locations in times when the ocean between them is warmer, the travel time should be reduced accordingly. This method averages ocean temperatures across depths, or ocean heat content, over large scales, and, in theory, repeating long-range propagation experiments with the same sources and receivers at the same locations would allow for measuring ocean warming across scales of thousands of kilometers, if sufficient samples were collected. ATOC has also been the basis for modeling studies that reveal the shift in sound propagation across large scales under different climate warming scenarios from global climate models (Dzieciuch, 1994).

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Climate Change Impacts on Underwater Acoustic Sources

Acoustic sources, or signals contributing to ocean soundscapes in different regions, will be shifted in several ways because of climate change. Passive acoustic monitoring networks contribute to our understanding of precipitation patterns and storms, particularly in more remote sections of the ocean where weather stations may not be available or as densely spaced (Pensieri and Bozzano, 2017).

The same marine life that acousticians and marine biologists are describing as major contributors to underwater ambient noise is under a dual threat from greenhouse gases shifting the physical and chemical parameters of their habitat as well as humans actively removing animals from the system for food. Some of these animals, such as corals and marine mammals, have been identified as endangered species, whereas others are identified as at risk from climate change impacts, in both cases meriting targeted conservation and restoration efforts. Acoustics has a key role to play in that effort, both in terms of monitoring marine life and as a means of enhancing results.

Conservation efforts in the past decade or so have been incorporating soundscapes to encourage larval recruitment and retention at restored coral reef sites (Lamont et al., 2022). Passive acoustic monitoring is becoming a more frequent tool in tracking marine conservation efforts and marine mammal species ranges and numbers. Passive acoustics is also used by fisheries ecologists to track individual fish calls and group spawning events (Souza et al., 2023) and even to track invasive versus native species in key environments (Amorim et al., 2023). Fish calls are reliably utilized to identify certain fish to the species level, and the underwater acoustics community has begun to gather representative recordings of fish vocalizations into an open access library of fish sounds to improve consistency across scientific studies (Looby et al., 2023).

Of particular interest, an observational study has shown that marine ecosystems respond to warmer seawater by increasing their acoustic output (Freeman et al., 2023). Snapping shrimp, a key contributor to ocean sounds, particularly in shallow near-shore areas, have been observed to increase their snap rate in warmer waters, with the snap rate doubling in association with 5°C of warming. This was initially observed from long-term passive acoustic monitoring data and then tested rigorously in laboratory experiments (Lillis and Mooney, 2022).

In another case of observed changes in ocean sounds linked to ocean temperature, a collection of long-term coral reef (**Figure 4**) soundscape records in both Hawai'i and Bermuda showed an overall increase in ambient noise in frequency bands associated with fish calls, parrotfish scrapes as they fed on coral polyps, and invertebrate activity with increasing temperature (Freeman et al., 2023). In the case of calls or vocalizations, the nonvocalization behaviors of invertebrate activity and feeding are incidental acoustic signals rather than intentionally produced sounds. Each of these type of acoustic signals was considered separately and filtered by their predominant frequency band, with fish calls being the lowest at 500-1,000 Hz followed by parrotfish scrapes at 1-2 kHz. Sound level as pressure spectral density in each frequency band was calculated over several years of data and compared with ocean surface temperature to identify this trend. Each individual metric showed the same positive correlation with ocean surface temperature.

Moreover, despite being situated in different ocean basins and latitudes, there was a remarkable overlap in midfrequency ambient noise (2-10 kHz) associated with invertebrate activity on coral reefs and seawater

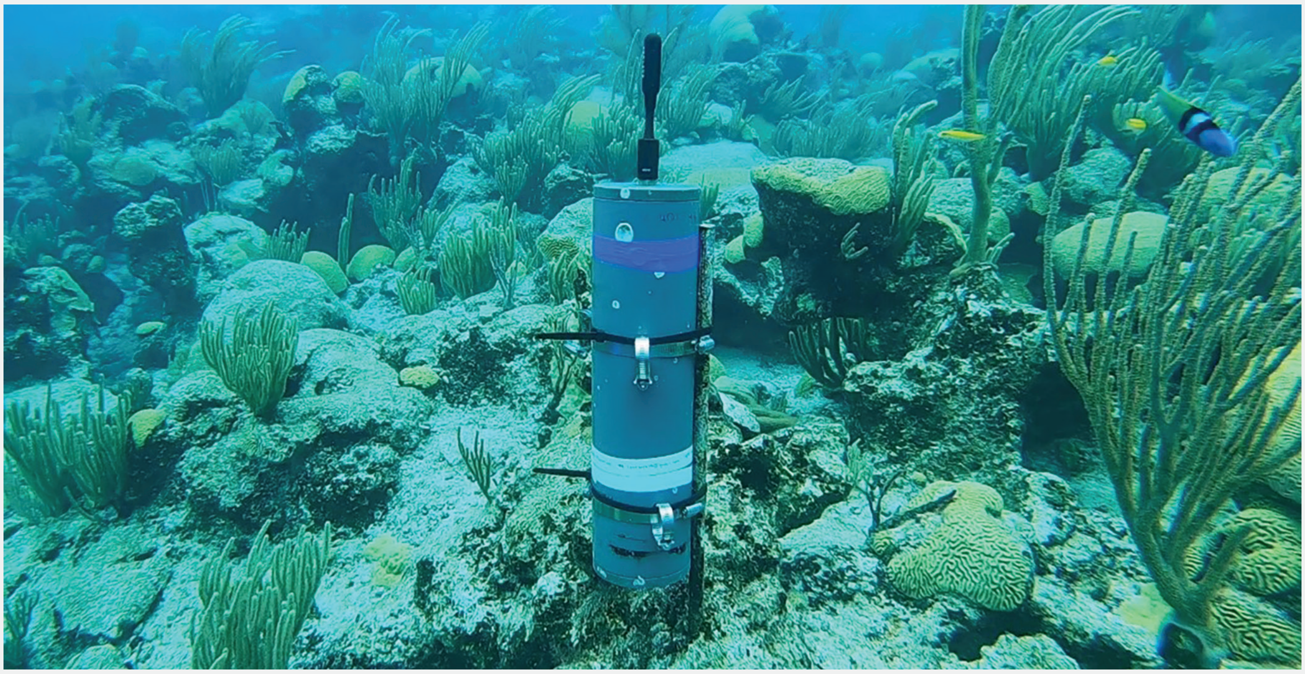

Figure 4. *Passive acoustic monitoring of temperate coral reefs in Bermuda. Self-contained hydrophone recording packages include the hydrophone (small black antennae on top of the instrument) attached to a waterproof housing that holds a receiver, data storage, and batteries. These systems are installed on the seafloor for months or years at a time and exchanged by divers to maintain the time series. Photo by L. Freeman.*

temperature. The species composition of coral reefs in Bermuda and Hawai'i are unique to each other, suggesting that the observed trend is not the response of one or two primary noisemakers but rather a broader trend in activity levels and sound production by invertebrates in reef environments as a function of water temperature. Other contributions to the soundscape such as physical noise from wind, rain, and storms were tested as well but did not show significant linkage to ocean temperature (Freeman et al., 2023).

The Arctic is being disproportionately affected by ocean and atmospheric warming due in large part to the positive feedback cycle of ice albedo, which is the ability to reflect solar radiation. As sea ice and land ice melt, they reduce in thickness and their albedo is also decreased. This leads to more heat transfer and faster melting. In this particularly dynamic environment, there is a confluence of shifting noise sources contributing to the soundscape and rapidly changing physical and chemical ocean parameters affecting sound propagation through water. A 2022 special issue of *The Journal of the Acoustical Society of America* on Ocean Acoustics in the Changing Arctic (see bit.ly/3ITvT9y) (Worcester et al., 2022) noted that acoustic systems have a special role to play in making measurements of the ice-covered Arctic Ocean.

Conclusions

Nearly all underwater environments are being affected by climate change and human activity, and effects on some regions are more pronounced than on others, such as we are seeing in the Arctic. In all cases, soundscape studies will help us better understand what is happening across space and time by taking advantage of the unique properties of sound propagation through seawater. Soundscapes are being used in coral reef restoration efforts both as a means of tracking ecosystem health and as a means of attracting fish and coral larvae to restored sites. Because the ocean is considered for a larger number of marine CO_2 removal efforts, soundscapes offer the ability to track impacts on native marine species as well as to monitor seawater temperature, pH, and chemical makeup as it affects acoustic propagation. There is a key interplay between understanding marine soundscapes and using that knowledge to support ocean stewardship, conservation, and climate mitigation efforts.

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