THE

Ocean Twilight Zone's Role in Climate Change

The Ocean Twilight Zone Team at Woods Hole Oceanographic Institution

OCEAN TWILIGHT ZONE

WOODS HOLE OCEANOGRAPHIC INSTITUTION

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This report represents an attempt to describe scientific knowledge that has been gained, highlight major questions that remain about the twilight zone's role in carbon sequestration, and suggest new considerations and tools for decision-makers that can shape future marine policy.

EXECUTIVE SUMMARY

The ocean twilight zone (more formally known as the mesopelagic zone) plays a fundamental role in global climate. It is the mid-ocean region roughly 100 to 1000 meters below the surface, encompassing a half-mile deep belt of water that spans more than two-thirds of our planet. The top of the ocean twilight zone only receives 1% of incident sunlight and the bottom level is void of sunlight. Life in the ocean twilight zone helps to transport billions of metric tons (gigatonnes) of carbon annually from the upper ocean into the deep sea, due in part to processes known as the biological carbon pump. Once carbon moves below roughly 1000 meters depth in the ocean, it can remain out of the atmosphere for centuries to millennia. Without the benefits of the biological carbon pump, the atmospheric CO_2 concentration would increase by approximately 200 ppm[1] which would significantly amplify the negative effects of climate change that the world is currently trying to curtail and reverse. Unfortunately, existing scientific knowledge about this vast zone of the ocean, such as how chemical elements flow through its living systems and the physical environment, is extremely limited, jeopardizing the efforts to improve climate predictions and to inform fisheries management and ocean policy development.

The biological carbon pump contributes to one of Earth's most valuable natural services—and is a challenging phenomenon for scientists to study because it involves complex physical, chemical, and biological processes deep in the mid-ocean realm. The latest findings from the Intergovernmental Panel on Climate Change (IPCC)[2] paints a grim picture for the future, if civilization is unable to keep global temperatures from rising. Upon release of the IPCC report in August 2021, the United Nations (UN) Secretary General declared it a "code red for humanity" and explained, "the alarm bells are deafening, and the evidence is irrefutable: greenhouse gas emissions from fossil-fuel burning and deforestation are choking our planet and putting billions of people at immediate risk. Global heating is affecting every region on Earth, with many of the changes becoming irreversible." Consequently, it is urgent to understand the ocean twilight zone's role in transporting carbon, how that transport could change as a result of climate change impacts on ocean health and resource extraction, and how those changes may influence our future climate.

The world of ocean policy development has recently awakened to the recognition of the critical role that our ocean plays in global climate. In response to a chorus of requests to the UN to include the ocean's role in climate change conference deliberations, the UN launched the Ocean and Climate Change Dialogue in December 2020. This dialogue is illuminating the nexus between ocean, climate and biodiversity regimes and suggesting various mitigation and adaptation strategies by which the ocean can play a central role in managing climate change.

Improved scientific knowledge about ocean twilight zone processes will serve as an invaluable resource to world leaders and policymakers as they make decisions on ocean and climate-related issues. Improved understanding of the ocean twilight zone will also be crucial for predicting future climate, conserving biodiversity and maintaining healthy ocean processes, managing fisheries, developing appropriate ocean and climate policies, designating marine protected areas, and supporting ocean-based solutions to climate change that are effective, long term, and have no negative ecological impacts.

For these reasons, increasing our knowledge of the ocean twilight zone—and managing its resources effectively—are essential elements in the portfolio of climate management strategies. The vast marine biodiversity and carbon sequestration services of the ocean twilight zone are critical to the health of humankind and our planet. As the recent proliferation in wildfires, floods and powerful storms around the globe reveal, we do not have decades to accomplish this goal. It is imperative to advance studies of the ocean twilight zone's link to climate now, or risk heading into a future without viable solutions. This report represents an attempt to describe scientific knowledge that has been gained, highlight major questions that remain about the twilight zone's role in carbon sequestration, and suggest new considerations and tools for decision-makers that can shape future marine policy.

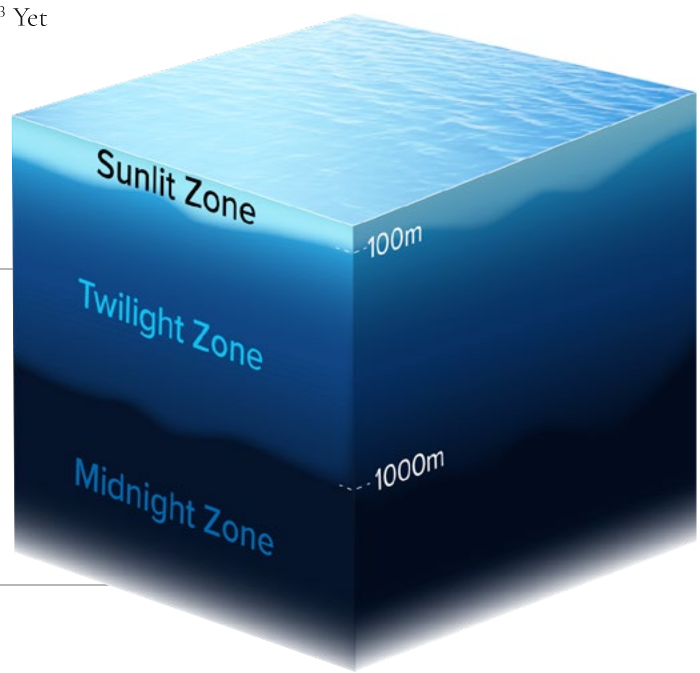
KEY FACTS

- The ocean contains roughly 50 times more carbon than the atmosphere, and roughly 20 times more carbon than land-based soil and plants.[3] It also has thus far absorbed 93% of the extra energy from the enhanced greenhouse effect, with warming now being observed down to the bottom of the ocean twilight zone (depths of up to 1000 meters).[4]
- The global ocean removes up to one-third of the excess carbon added to the atmosphere by human activities each year through a combination of chemical, physical, and biological processes.[5]
- The ocean twilight zone plays a crucial role in regulating Earth's climate. It is one of the largest reservoirs of life on our planet, encompassing approximately 20% of the global ocean volume. The marine organisms it contains are responsible for storing more carbon than the terrestrial biosphere.[6]
- The vast majority of the carbon that makes it from the surface to the deep ocean is transported as "marine snow"—tiny clumps of carbon-rich organic material, animal feces, and microbes that sink down through the water.[7]
- Biological processes in the ocean twilight zone control the movement of 2-6 billion metric tons of carbon annually from the surface down to the deep ocean, where it can remain sequestered for hundreds to thousands of years.[8]
- The biological processes that move carbon from the surface into the twilight zone include the largest animal migration on Earth. Trillions of twilight zone animals travel from the twilight zone to the ocean's surface each night to feed, then return to the deep before dawn with carbon-rich food inside them. This phenomenon is known as the Diel Vertical Migration or DVM.
- Improved understanding of the ocean twilight zone's role in global climate talks will be essential for crafting responsible and sustainable ocean policies to achieve stabilization of greenhouse gas concentrations in the atmosphere (at a level that would prevent dangerous anthropogenic interference with the climate system) as well as sustaining a healthy, productive and resilient ocean.

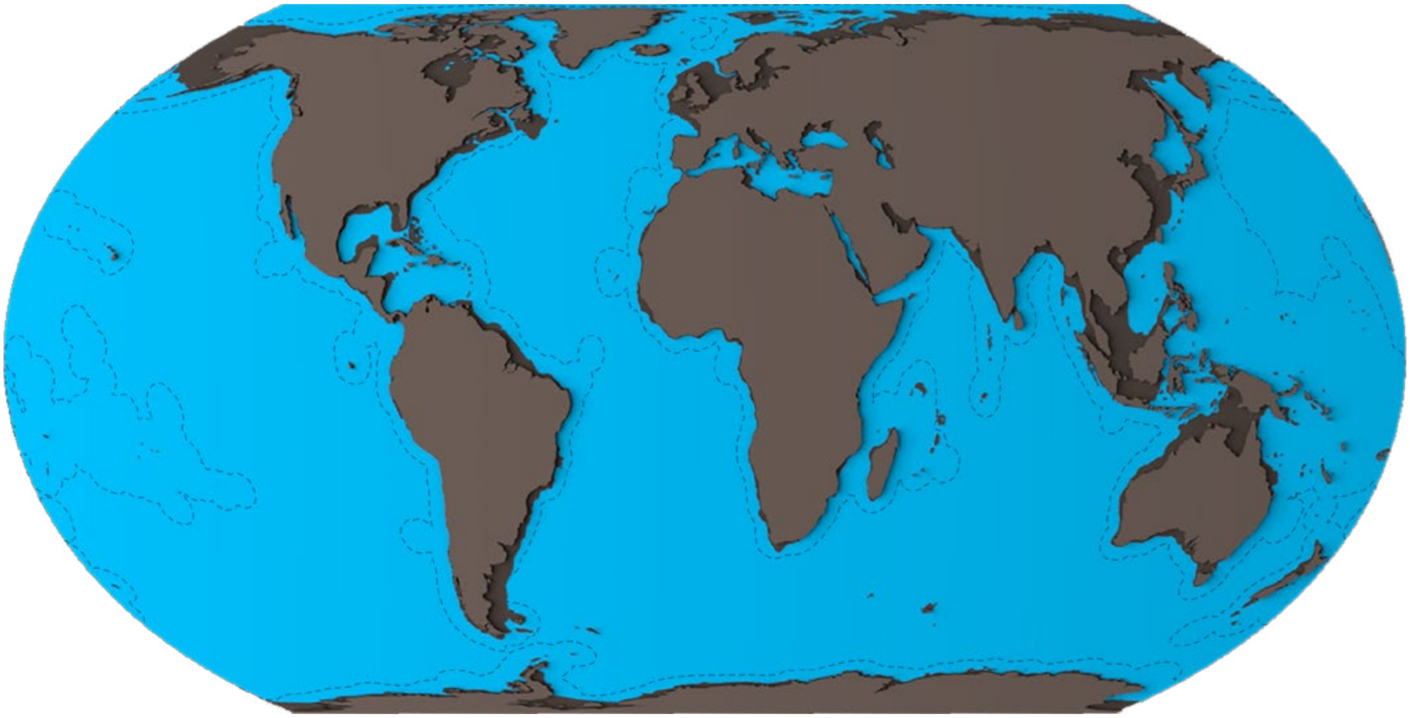
ECOLOGICAL SIGNIFICANCE OF THE OCEAN TWILIGHT ZONE

Life in the ocean twilight zone includes microbes, tiny animals known as zooplankton, crustaceans (e.g. crabs, shrimp, krill), fish, squid, and many kinds of gelatinous animals. The twilight zone is also home to some of the largest populations of fish in the world's ocean—including 31 species of bristlemouth fish, which are considered to be the most abundant vertebrate on Earth. In fact, estimates of global fish biomass in the twilight zone conclude that this mid-ocean habitat could hold more than 95% of all fishes in the ocean by weight.[9] Early estimates used the catch from trawl nets to estimate biomass but it was subsequently discovered that twilight zone fish exhibit escape reactions to nets, resulting in gross underestimates of biomass when using that method.[10] More recent estimates using bioacoustics (sonar) indicate that biomass of twilight zone fishes may be as high as 16 gigatonnes.[11] However, the large range of uncertainty in twilight zone fish biomass presents a significant challenge in refining the role of oceans in climate and this knowledge gap requires urgent scientific effort. "Mesopelagic fishes remain one of the least investigated components of the open-ocean ecosystem, with major gaps in our knowledge of their biology and adaptations, and even major uncertainties about their global biomass."[12] Many of these fish, along with invertebrate organisms in the zone, take part in the diel vertical migration (DVM), a phenomenon in which trillions of marine animals move from the twilight zone to the surface and back again on a daily basis, helping to transfer carbon out of the upper ocean and into deeper waters. Although evidence indicates that this large-scale process has a significant impact on global climate, it is poorly understood by scientists, meaning that it will be a critical element for future study in order to understand how human impacts (such as fishing, pollution, deep sea mining, and climate change impacts) may affect these processes.

The ocean twilight zone is also characterized by globally-occurring 'deep scattering layers.' These are belts of living organisms, occurring below the surface, that cause sound waves to scatter, thereby producing echoes in depth sounders. The deep scattering layers are composed of dense aggregations of fishes, squids, and zooplankton that provide an essential food source for numerous commercially important fishes including tuna and swordfish as well as iconic ocean predators such as whales, dolphins, sharks and seals.[13] Yet despite its ecological importance, the ocean twilight zone remains understudied and there is much to learn about species, communities, life histories, behaviors and complex food webs.



The ocean's mesopelagic zone, also known as the ocean twilight zone, is located roughly 100 to 1000 meters below the surface. It begins just beneath the sunlit waters of the upper ocean and ends at the permanently dark waters of the midnight zone. The mesopelagic exists throughout the deep ocean beyond shallow continental shelves and is located mainly on the high seas, but it also extends into the 200-nautical-mile exclusive economic zones (EEZs) of many nations, including those of Small Island Developing States (SIDS). Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution



THE MARINE CARBON CYCLE

The ocean twilight zone acts as an important conduit for moving carbon from the ocean's surface into deeper waters where it can remain sequestered for centuries or more. This movement is driven by a variety of biological, chemical, and physical processes, and it deeply influences global climate.

Only a portion of CO_2 emitted into the atmosphere remains there. Ocean (and terrestrial) environments act as "sinks" for atmospheric CO_2—parts of the physical system that serve to sequester carbon and act as a reservoir. Approximately 50% of CO_2 emissions remain in the atmosphere and approximately 25% is absorbed in the oceans. According to the IPCC Special Report on Carbon Dioxide Capture and Storage, "the oceans contain roughly 50 times the quantity of carbon currently contained in the atmosphere and roughly 20 times the quantity of carbon currently contained in plants and soils."[14] To complicate matters, there is significant spatial and seasonal variability across ocean basins in how much CO_2 is absorbed by the oceans.

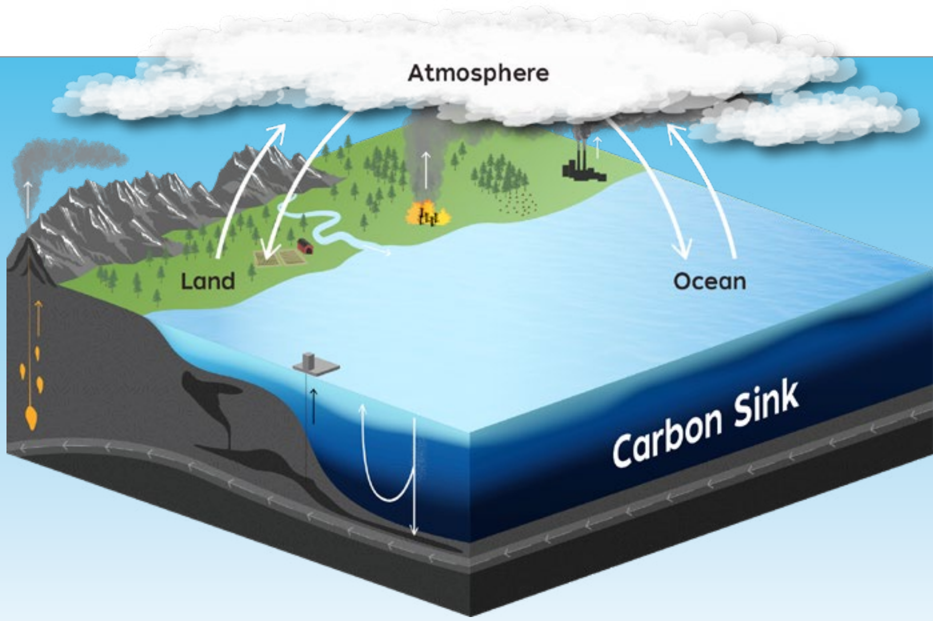
Unfortunately, we can't count on the CO_2 absorption services provided by either oceanic or terrestrial environments that are currently serving to remove substantial quantities of this potent greenhouse gas (GHG) from our atmosphere, to continue undisturbed into the future. Emerging scientific knowledge indicates a strong possibility that we can expect CO_2 absorption efficiency to decline, which would lead to a faster rate of atmospheric CO_2 accumulation.[15] The ocean's role in absorbing atmospheric CO_2 emissions has clearly been valuable to society by reducing the greenhouse effect but it comes at a high cost to the health of our oceans. Increasing CO_2 in the ocean alters the chemistry of seawater (an effect known as ocean acidification) which is of present and future concern due to the negative impacts it imparts on marine life.

Blue on this map indicates the approximate extent of the twilight zone across the global ocean. Parts of the twilight zone fall within the 200-nautical-mile exclusive economic zones (EEZs) of many nations (shown by dotted lines above), but most of it lies in the deeper waters of the "high seas," and is beyond national jurisdiction. Map by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution. PROJECTION: Equal Earth, SOURCES: naturalearthdata.com

Much of the carbon introduced into the ocean through atmospheric exchange of CO_2 is subsequently transported, in the form of dissolved inorganic carbon (DIC), to deep water by the ocean's thermohaline circulation, where it is sequestered for hundreds to thousands of years. This phenomenon is known as the 'solubility pump.' Adding to the carbon sequestering power of the solubility pump is the multifaceted 'biological carbon pump (BCP)'. The ocean twilight zone plays a key role in the BCP. A principal component of this biological pump is the gravitational sinking of "marine snow", the carbon rich organic materials that are formed in the surface layer and settle down through the twilight zone. The dark environs of the twilight zone are key for determining how much carbon makes its way to the deep ocean. It is the home to a staggering array of organisms—and each day, some of them, in fact up to trillions of those animals, migrate from the depths to the shallows and back again, facilitating the shuttling of carbon into the deep ocean. Together, the biological, physical, and chemical processes within the twilight zone transport 2 to 6 billion metric tons of carbon each year out of the twilight zone and into the deep ocean, an amount that's comparable to the United States' entire annual carbon emissions.[16], [17]

In the sunlit surface layer of the ocean, marine plants use photosynthesis, and the energy of the sun, to convert CO_2 to organic molecules that make up their cells. This is known as primary productivity and it forms the base of the ocean food web. These plants are then either consumed by animals in the food web or they die and decay, transferring their carbon into another living organism or into the atmosphere. Some of the carbon they absorb is returned to the ocean and released back into the atmosphere through cellular respiration and decay, and some enters a complex marine food chain, where it can be transported into deep water and sequestered for hundreds to thousands of years. When it reaches the deep ocean floor, it provides a source of carbon and energy for seafloor (benthic) organisms and much of it is incorporated into sediments, thereby remaining out of the atmosphere for millennia.

When larger animals die or defecate, the carbon in their bodies and feces sinks down into deeper water. In most places, if this matter sinks below 500 meters (1640 feet), the carbon will likely stay out of the atmosphere for hundreds of years. If it sinks below 1,000 meters (3280 feet), however, the carbon can remain in the deep ocean for upwards of a thousand years. Researchers have discovered that sequestration timescales for carbon, at various depths in the ocean, are highly variable depending upon specific ocean basins.[18]



A simplified view of the global carbon cycle. Arrows represent a variety of ways that carbon moves between land, the atmosphere, and the ocean. Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

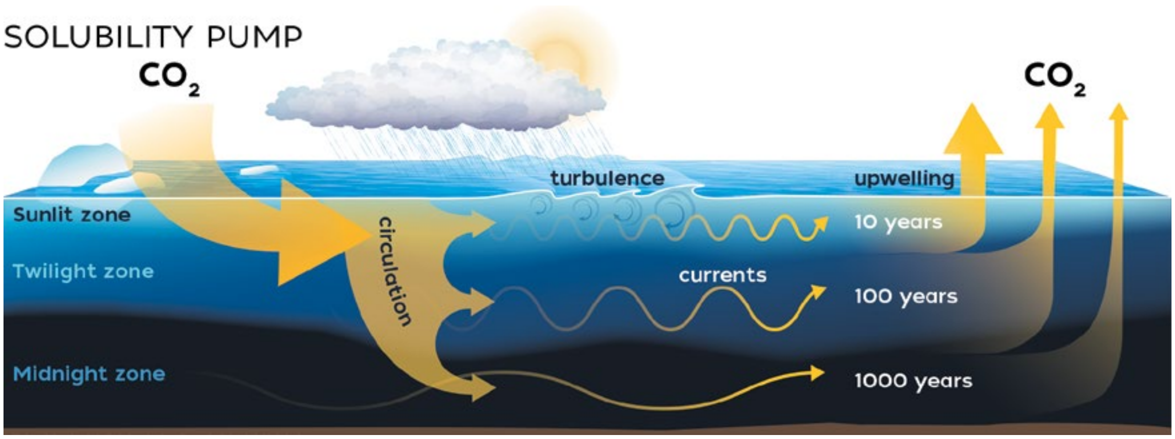


Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

Solubility Pump

Many different gases dissolve in seawater including oxygen, nitrogen and carbon dioxide. Solubility of CO_2 is strongly dependent on temperature, among other factors. The colder the water, the more CO_2 it can hold. Indeed, most of the CO_2 from atmospheric sources is dissolved in cold water of the high latitudes (particularly so in the north Atlantic). Each year, the global ocean absorbs about 25% of all carbon emitted into the atmosphere from human activities.[19] Alarmingly, the efficiency of seawater to dissolve CO_2 is expected to decrease as the ocean continues to warm. In polar regions, where solubility of CO_2 is high, sea ice formation leaves the surrounding waters very salty and dense. The dense water then sinks, generating a 'thermohaline' circulation that continuously moves water equatorward in the deep ocean (known as the global conveyor belt). Therefore, the deep sea stores vast quantities of dissolved inorganic carbon (DIC) on long timescales. This process of atmospheric CO_2 dissolving and reacting in the sea surface to form DIC then being transported into the deep sea by wind and thermohaline circulation is known as the 'solubility pump.' It is important to note that CO_2 also outgasses back into the atmosphere (just as a carbonated beverage becomes flat after opening the container), therefore the balance of carbon between ocean and atmosphere is the important factor in relation to how much GHG is in the atmosphere at any given time.

Biological Carbon Pump

Once the solubility pump introduces carbon into surface waters, the ocean twilight zone's biological carbon pump (BCP) plays an important role in the rapid removal of a fraction of that carbon further downward into the deep sea. The physical, chemical, and biological processes that take place in the zone start with the transport of upwards of 12 billion metric tons of carbon annually out of the surface ocean.[20] Most of that carbon goes to feeding the twilight zone marine organisms, leaving roughly 10% to exit the twilight zone and reach the deep sea, effectively keeping heat-trapping GHGs out of the atmosphere. The BCP is not a single process, rather it is a collective of processes that synergistically influence the transport of carbon deep into the ocean that in turn helps regulate global climate.[21]

Essentially, there are three major pathways that comprise the Biological Carbon Pump (BCP):

1. Gravitational Pump,
2. Mixing Pump, and
3. Migrant Pump.

BIOLOGICAL CARBON PUMP

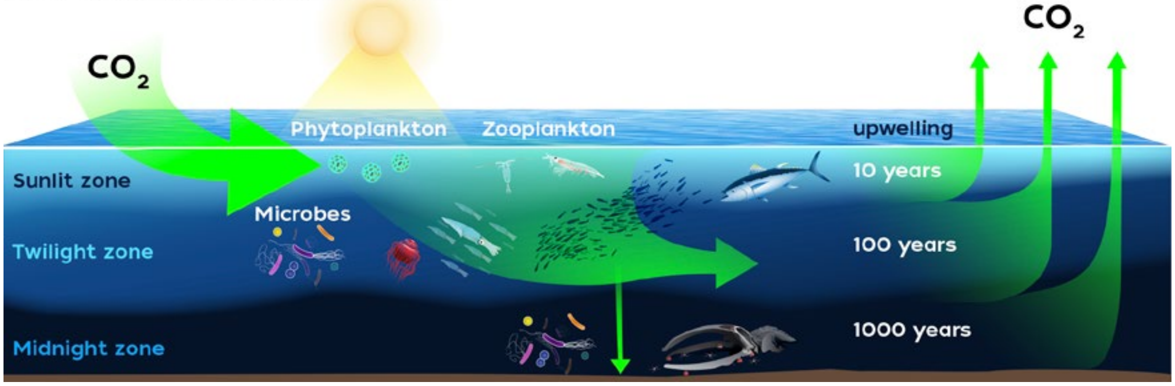
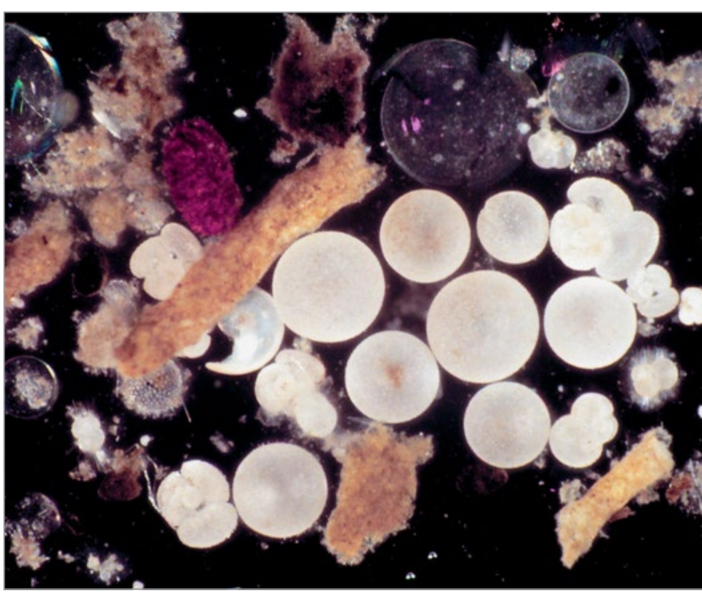


Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

GRAVITATIONAL PUMP

The largest path of the BCP is the gravitational pump, which refers to the sinking of organic carbon in various size particles from the surface layer of the ocean to depth. This form of carbon is called sinking particulate organic carbon (POC) as it can be collected by a filter, and is of a size and density that allows it to sink with gravity. It is also known as 'marine snow' since much of it is visible with the naked eye and has an appearance similar to snowflakes falling through air. It is composed of clumps of dead plankton, bacteria, fecal pellets, and other particles rich in organic carbon. As these particles sink from sunlit surface waters down into the deep sea, they provide food for bacteria and other twilight zone organisms along the way. The majority of carbon that sinks below 500 meters is carried within marine snow by the force of gravity. Roughly 90% of marine snow is consumed in the twilight zone, where it cycles through the food web.[22] A small percentage, however (about 0.1 to 1 billion metric tons of carbon each year), sinks below 1,000 meters, where it is sequestered out of the atmosphere for centuries to millennia.[23]

Left: A microscope image of marine snow shows cylindrical fecal pellets and other aggregates, planktonic tests (round white objects), transparent snail-like pteropod shells, radiolarians, and diatoms. This sample, recovered in 1977 from the bottom of the Sargasso Sea, showed that "packages" of carbon and other nutrients could descend to the seafloor through the water column. Right: A sample collected by WHOI's Twilight Zone Explorer instrument includes an intact fecal pellet, most likely from a fish. A pellet like this would likely sink very quickly, carrying carbon with it.



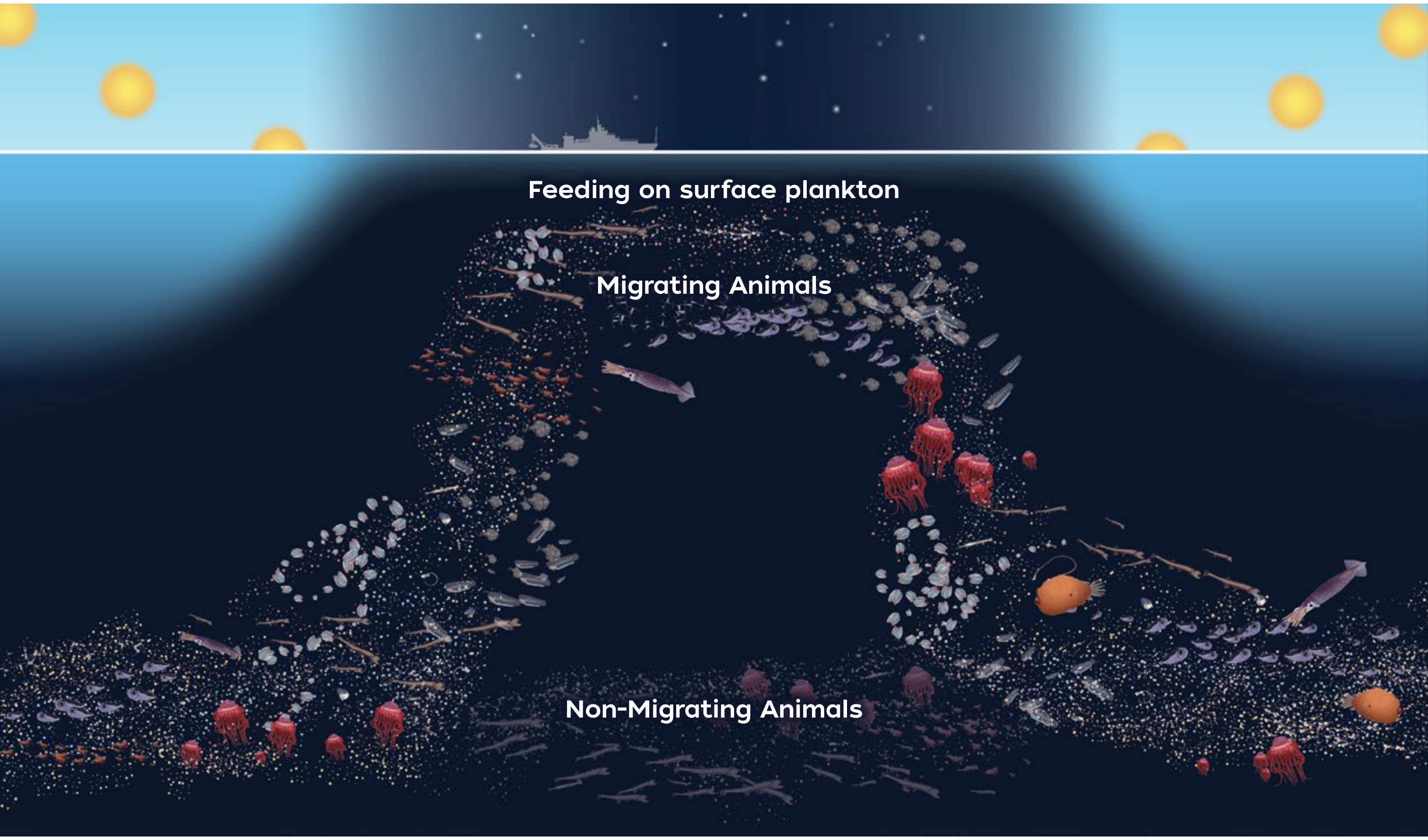
Courtesy of Susumu Honjo, © Woods Hole Oceanographic Institution

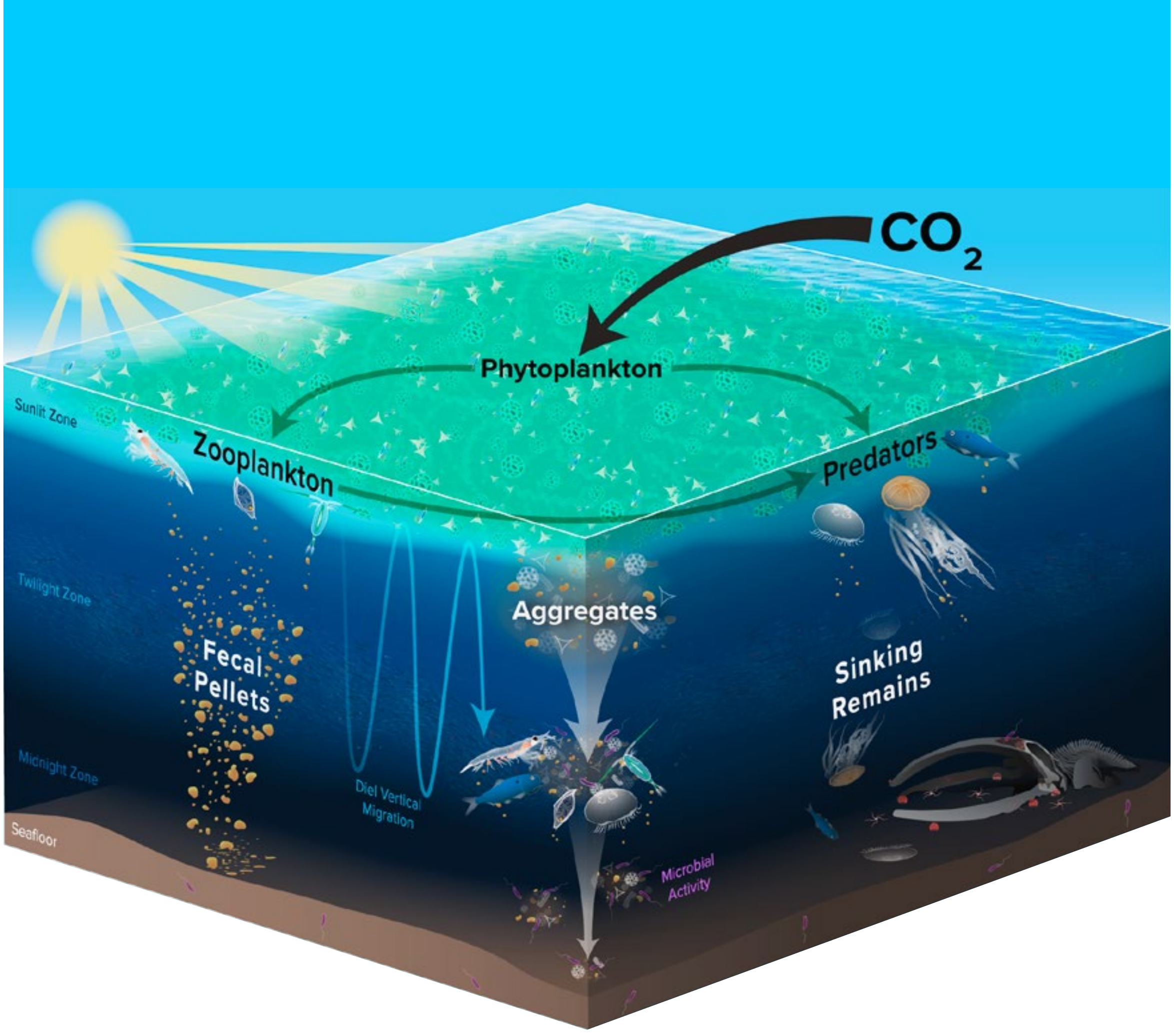
MIXING PUMP

The Mixing Pump moves non-sinking forms of organic carbon from the sunlit layer of the ocean, where it is formed, to deeper depths. This organic carbon is dissolved in sea water and referred to as Dissolved Organic Carbon (DOC), or it is entrained in buoyant Particulate Organic Carbon (POC). This carbon is transported downward by mixing of water from physical processes such as storm-driven turbulent seas and downwelling currents. Carbon-rich surface waters are therefore 'mixed' in the water column and the deeper the carbon penetrates the water column, the longer it will remain sequestered in the ocean.

MIGRANT PUMP

The diel vertical migration (DVM) is a major part of the ocean's BCP. As the sun sets each day, many animals living in the twilight zone—including fishes, gelatinous zooplankton, crustaceans, and others—rise up to the surface *en masse* to feed on carbon-rich plankton and other organisms. As the sun rises and the upper ocean is illuminated, they descend back to the relative safety of the twilight zone's darker waters, where they stay until night comes again. Through that daily vertical migration cycle, organisms actively transport carbon. This phenomenon represents the largest migration of animal life on Earth. Although DVM may help to fast-track carbon out of the surface ocean and into deep water, scientists are only just starting to understand its full impact on global climate.





The figure above illustrates the ocean food web processes that drive the transformation and partitioning of carbon among various reservoirs. Dissolved inorganic carbon enters the ocean as CO_2 which is subsequently converted into particulate and dissolved organic carbon by phytoplankton in the sunlit layer known as the Epipelagic Zone. Organic carbon becomes a source of food for zooplankton (small animals and immature stages of larger animals). In turn, the zooplankton respire CO_2 back into the water. A fraction of phytoplankton carbon is exported from the surface ocean, either as sinking fecal pellets or as aggregates (gravitational pump). Dissolved organic carbon is mixed into the ocean twilight zone by moving water masses (mixing pump). Zooplankton also contribute to carbon export through their diurnal (and seasonal) migrations (migrant pump) from the surface layer into the depths of the ocean twilight zone. Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

In surface waters, the migrators dine on the microscopic plankton and other organisms. As light returns to the upper ocean, well-fed twilight zone animals migrate back to darker waters carrying their meal—and the carbon it contains—inside their stomachs.

The predictive understanding of how these ecological, biogeochemical and physical oceanographic processes work together to sequester carbon on human-relevant time scales is critical for monitoring and predicting changes to the ocean's carbon cycle, especially in a changing climate.

The three primary pathways of the BCP (gravitational pump, mixing pump and migrant pump) described above, that are responsible for transporting carbon from surface waters to greater depths, urgently need more scientific research to better understand their magnitude and controls. A comprehensive scientific effort to quantify the various components of the BCP is needed to develop important climate diagnostic and predictive models for the export and fate of Net Primary Productivity (the production of organic carbon through the process of photosynthesis).[24]

THE IMPERATIVE TO EXPAND UNDERSTANDING OF TWILIGHT ZONE PROCESSES

Answering scientific questions about how carbon moves through the ocean twilight zone will help scientists predict changes in global climate in the future. This can benefit humankind by...

Solving Societal Problems by Closing Knowledge Gaps

To underscore the urgent scientific need for improving our understanding of the BCP processes, consider this: civilization's present capabilities to quantify the export and fate of ocean Net Primary Productivity from satellite sensors and our ability to model these processes are extremely limited. To highlight this climate science deficiency, estimates of global carbon export flux from the surface to the deepest depths of the ocean range from 1-7 billion metric tons of carbon per year. This massive uncertainty range equates to an amount of carbon comparable to the annual perturbations in the global carbon cycle due to all human activities.[25]

Despite a wave of new international research focused on the twilight zone, broad questions remain about its role in the global carbon cycle. On the one hand, animals that migrate daily between the twilight zone and the surface to feed may increase the flow of carbon to deeper waters. On the other hand, bacteria and larger organisms consume carbon-rich marine snow as it sinks downward, recycling it in the twilight zone and reducing the amount sequestered in the deep ocean. Further confounding matters, some marine life like microscopic coccolithophores release CO_2 in the process of creating their carbonate shells, effectively adding carbon back into seawater. As a result of these conflicting processes, the net contribution of all organisms living within the twilight zone to carbon sequestration is still unclear. Being able to say with greater certainty how carbon moves through the twilight zone—and what effect this transport has on climate itself—will directly improve our ability to model Earth's climate systems, strengthening a critical tool for coping with an uncertain climate future.

Categories requiring additional research and knowledge development include:

Carbon Flow - Advanced understanding of the twilight zone's role in the global carbon cycle will be essential for estimating carbon sequestration and therefore informing policies to mitigate future climate change effects. There are significant knowledge gaps on the impact of biological processes of the twilight zone on the global carbon cycle.

Biological Carbon Pump - Gravity transports carbon, entrained in marine snow, from the surface ocean to the deep sea. Yet as those particles pass through the twilight zone, many are consumed, which prevents them—and the carbon they contain—from sinking deeper. Further research is needed to determine the net effect that biodiversity and biomass plays in carbon transfer to the deep ocean.

Food Webs and Carbon - The feeding behavior of marine organisms—and the amount they consume near the surface versus at-depth—affects how much carbon reaches the deep ocean. In some cases, feeding behavior could enhance the downward movement of carbon—in other cases, it may prevent carbon from reaching deeper waters. More knowledge is needed regarding how the variability in marine food webs affects carbon flowing through the twilight zone.

Impacts of Commercial Activity - Through vertical migration and feeding, fish in the twilight zone play a role in the global carbon cycle, yet their effects on carbon transport to the deep ocean are not yet well understood. If fishing the twilight zone and/or mining the seafloor for minerals (thereby releasing sediment plumes in the midwater) becomes commercially viable and expands to large-scale operations, there is currently no way to estimate the impacts on twilight zone ecosystems or global climate. It is imperative to study the effects industrial-scale fishing, mining, or carbon capture technologies may have on the ecology of the twilight zone and its role in the marine carbon cycle.

Enabling Smart Decision-making

Increased understanding of the ocean twilight zone will provide important information for creating effective climate and ocean-related policies. These include, but are not limited to, efforts like setting emission control targets, designing carbon tax policies and trade-off analyses, conducting environmental assessments, designating marine protected areas, developing other measures to conserve and sustain marine biological diversity, and supporting clean energy projects. Better knowledge of how the zone processes carbon will also provide data to plan for climate change mitigation, abatement and community adaptation.

Yielding Economic Benefits to Society

Even a modest increase in scientific understanding of the twilight zone's role in global climate has direct economic benefits. According to a recent study by WHOI researchers, advancements in scientific knowledge about carbon flow processes in the ocean twilight zone could save about $500 billion worldwide—or roughly the national GDP of Thailand or Sweden.[26] These savings would materialize as increased knowledge of the twilight zone drives more accurate predictions of future climate change, which in turn allows for more effective assessment of its impacts. Improved anticipation of future losses, for example, could inform the development of protective measures like flood defenses or improved choice of location for development, thus reducing climate-related damages to infrastructure and property.

Expanding Environmental Assessments

The United Nations Sustainable Development Goals (SDG 14.2) call for "sustainably managing and protecting marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and [taking] action for their restoration in order to achieve healthy and productive oceans."[27] In order to accomplish these goals, it will be necessary to improve environmental assessments within the ocean twilight zone, and to establish a robust baseline for future comparison of human impacts. Increasing scientific knowledge of the zone's biology—and its role in carbon sequestration—will be a central component of building these assessments from national to global scales.[28]

Establishing a Three-Dimensional Marine Reserves System

In order to build effective ecological conservation programs—like marine protected areas or other area-based management tools—decision-makers will need to take into account the twilight zone's unique function in the marine ecosystem. Gathering new information about its role in the marine biological carbon pump, for instance, could help to improve knowledge on the carbon sequestration benefits of new conservation efforts and by addressing food web and other connections from the deep seabed to surface waters, enhance the resilience of marine ecosystems to climate change. With the pressures of sustainably serving our increasing human population with ocean resources, the case for creating a practical international system of marine reserves for the open ocean (including the full water column and the seafloor) is more compelling today than ever.

IMPENDING THREATS TO THE NATURAL SERVICES OF THE OCEAN TWILIGHT ZONE

Climate Change Impacts

The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report concluded that the ocean has thus far absorbed 93% of the extra energy from the enhanced greenhouse effect, with warming now being observed down to the bottom of the ocean twilight zone (depths to 1,000 m).[29] In response to the heat absorption, the ocean is becoming increasingly more stratified (layers of water that prevent mixing due to different properties of water masses), ocean current patterns are changing, and ocean 'dead zones' (areas depleted of oxygen) are growing in size and number. A study published in *Science* concluded that there were approximately 400 dead zones worldwide at the time of the study and that the number of dead zones has doubled each decade since the 1960s.[30]

Additionally, warming of the ocean has driven changes in the geographical ranges of marine species and shifts in growing seasons, as well as in the diversity and abundance of species. Furthermore, ocean temperatures and current systems play a pivotal role in global weather patterns. Weakened ecosystems increase human vulnerability in the face of climate change and undermine the ability of countries to implement climate change adaptation and disaster risk reduction measures, including those provided for in Nationally Determined Contributions (NDCs) under the Paris Agreement on climate change.

CO_2 emissions absorbed into the ocean are increasing the acidity of seawater (known as ocean acidification). Ocean acidification reduces the ability of marine organisms, such as corals, plankton and shellfish, to build their shells and skeletal structures. It also induces physiological stresses (such as impeded respiration and reproduction) and reduces growth and survival rates during the early life stages of some species. This is remarkable in the context that human industry, over just two centuries, has managed to destabilize the carbonate chemistry of the ocean, which has been in a relatively steady state for hundreds of thousands of years.[31] This situation will get worse before it gets better. Ocean acidification has already increased by 30% from pre-industrial levels and could increase another 120% by the end of the century.[32]

What may be affected by ocean acidification in the ocean twilight zone? Deep ocean waters are inhabited by two major types of zooplankton (tiny drifting animals) that build shells from calcium carbonate: foraminifera and pteropods. These two types of zooplankton, albeit small, play a large role in food webs as well as in the carbon cycle. It is yet unknown whether these animals will be able to adapt to increasingly acidic water or whether there will be major disruptions in their life history.

THERE IS A COST TO THE BENEFIT OF THE OCEAN ABSORBING CO_2 EMISSIONS: OCEAN ACIDIFICATION

The ocean's service in capturing and storing carbon has benefited society by slowing the accumulation of atmospheric CO_2 and, therefore, the pace of global warming. However, this comes at a societal cost. Increasing CO_2 in the ocean alters the chemistry of seawater (an effect known as ocean acidification) which is of present and future concern due to the negative impacts on marine life.

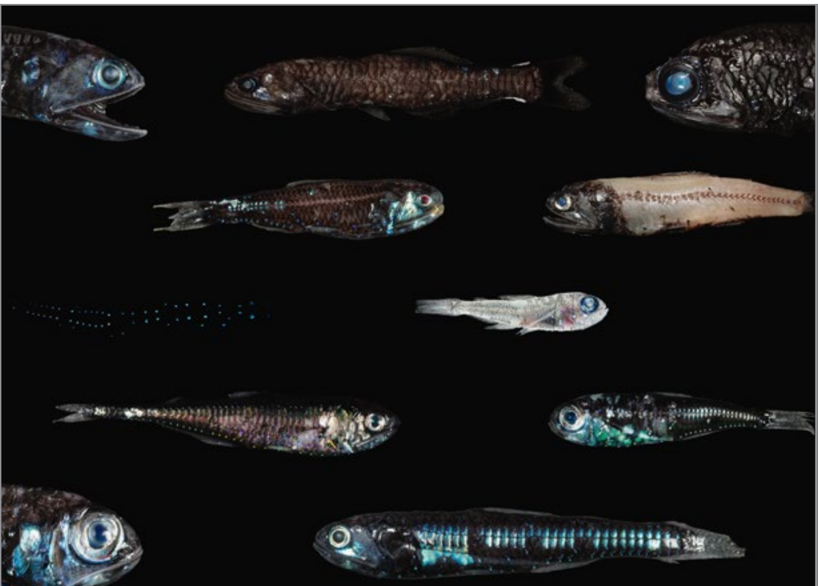
The term, ocean acidification, does not mean that ocean water is an acid (a substance with pH less than 7). Rather, its pH averages approximately 8.1 (in the 'basic' or 'alkaline' range) today and is predicted to drop to around 7.7 by the end of the century, a number that is still in the alkaline range. The term 'ocean acidification' refers to the decrease in pH of seawater over time, trending towards acidity. If humans had the luxury of time to wait until the ocean's pH stabilizes, we would eventually observe equilibrium in about a million years. This will happen through the slow dissolution of carbonate sediments on the bottom of the ocean and the weathering of rocks on land plus eventual mixing of surface and deeper waters.

Ocean Twilight Zone Fisheries

Without conducting thorough environmental impact assessments leading to subsequent establishment of an effective international fishery management framework, based on solid baseline information, commercial fishing in ocean twilight zone waters could inadvertently have a substantial impact on the marine carbon cycle.[33] Fish and other organisms in the twilight zone help to transport more than 25% of global atmospheric carbon emissions into the deep oceans each year. There is a compelling need for improved scientific understanding of the role of twilight zone fish and other organisms to be able to supply essential parameters for fisheries management. Detailed scientific knowledge of fish biomass, reproduction and population growth rates (for example) are unknown, making it difficult to predict the risks associated with large-scale commercial fisheries operations.

Upper estimates of the fish biomass in the twilight zone is approximately 15 billion metric tons of fish, or about 95% of all fish in the ocean by weight, making it potentially a very attractive target for commercial fishing,[34] especially to gather raw materials for fish oil and fish meal (to be used in nutraceutical and pharmaceutical production and feed for agriculture and aquaculture, respectively). At the moment, large-scale commercial fishing operations have yet to be put into place, primarily due to the costs and technological complexities of fishing such great depths and the relatively small size of the fish that live in the zone.[35] If a mid-water fishery becomes economically viable, widespread exploitation of the twilight zone ecosystem could soon be a reality, in light of the world's increasing demand for fishmeal and fish oil.

Left: Lanternfishes come in a variety of shapes, sizes, and forms, all of which share similar types of bioluminescent organs placed throughout their bodies. These fish are a food source for commercially important surface species such as bigeye and yellowfin tuna. Photo by Paul Caiger, ©Woods Hole Oceanographic Institution. Right: The Elongated bristlemouth (Sigmops-elongatus), one of the most abundant types of fish on the planet, lives primarily in the ocean twilight zone. Photo by Paul Caiger, © Woods Hole Oceanographic Institution



Ocean Pollution

The oceans are an end point for the waste products of civilization. Trace elements (e.g. arsenic, mercury, cadmium and lead), persistent organic pollutants (e.g. dioxins, furans, and biphenyls), and problematic lipid compounds (i.e. wax esters and erucic acid) have all been found in mesopelagic organisms at various levels.[36] In addition, microplastics have been found in the digestive tracts of mesopelagic fish. These undesirable contaminants should be fully evaluated before twilight zone organisms are permitted for use as aquaculture feed or to process fish oil for human consumption.

Seabed Mining

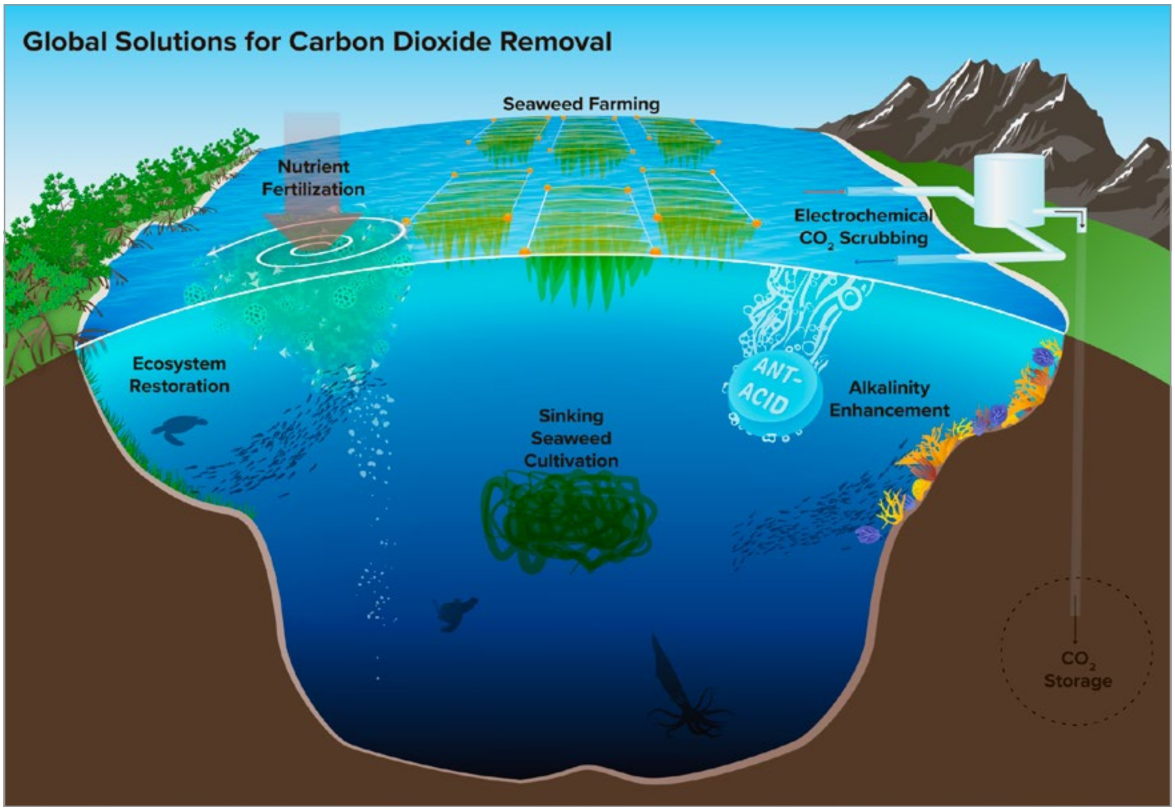
Over the next few decades, demand for minerals used in electronic devices should continue to grow. Technologies are being developed to mine the seabed to meet this demand, although widespread seabed mining is not yet occurring. Knowledge of deep seabed mining's potential environmental impacts is also under development, though many fundamental scientific questions remain unstudied. What is clear is that deep sea mining would inevitably disrupt large swaths of the seafloor ecosystem, and could eject plumes of sediment and contaminants into the midwater. The impacts of these new plumes on the twilight zone ecosystem could be extensive in individual organisms, causing reduced feeding, respiratory distress, buoyancy issues, direct toxicity, and other potential harms.[37] Mining-generated plumes may distress twilight zone organisms by clogging respiratory and olfactory surfaces. Suspension feeders like crustaceans, polychaetes, and salps, which already filter small particles from the water, could suffer from a diluted food supply as inorganic sediments replace their normal fare. If these plumes alter twilight zone species' behavior or ability to move carbon into the deep ocean, they may also, by extension, affect global climate. Before widespread seabed mining operations are permitted, it will be imperative to understand the effects on the twilight zone itself.

Carbon Dioxide Removal Technologies

If atmospheric CO_2 levels continue rising at current rates, the IPCC expects the amount of carbon removed from the atmosphere by the ocean to decline steeply by the year 2100. That reduced absorption capacity will result in increased rates of sea level rise, more severe weather events and acceleration of global warming by removing less CO_2 from the atmosphere.[38]

Ocean-based Carbon Dioxide Removal (CDR) technologies aim to prevent this extended impact by removing greenhouse gases from the ocean and accelerating their sequestration in the deep sea. This can be accomplished in a number of ways, most of which involve manipulating the ocean's biological, physical, and chemical processes. Examples of ocean-based CDR include: farming kelp; planting seagrasses or mangroves; injecting CO_2 into the midwater or seabed; fertilizing seawater with nutrients like iron, phosphorus, and nitrogen; depositing crop waste or other biomass on the ocean floor; and artificially changing ocean upwelling to bring cold, nutrient-rich water to the surface.[39]

Although the concept of ocean-based CDR dates back to the mid 1970's, it has yet to be implemented successfully on a large scale, and little is known about the efficacy or risks posed by such interventions. Intentional changes in ocean chemistry due to CDR may lead to shifts in ocean ecology resulting in undesirable consequences. Still, interest in large-scale ocean-based CDR strategies is increasing and may likely be attractive for



Conceptual and Experimental Methods to Sequester Carbon in the Ocean. Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

CDR technology development. Given the limits to carbon storage on land, enhancing ocean sinks has great potential. To avoid unintended consequences and assess the potential impacts of CDR on ocean ecosystems and global climate, it is critical for scientists to develop ways to monitor ocean processes at large scales. At the moment, however, researchers do not yet have the necessary technology—or sufficient scientific understanding of marine ecosystems like the twilight zone—to be able to comprehensively assess the impacts of CDR to the ocean. However, a new consensus study report conducted by the National Academies of Sciences, Engineering, and Medicine (NASEM) assesses the feasibility, cost, and potential impacts of ocean-based carbon dioxide removal approaches and recommends the establishment of a U.S. CDR research program.[40]

MEASURING THE VITAL SIGNS OF OUR OCEANS

The Woods Hole Oceanographic Institution is establishing an Ocean Vital Signs Network (OVSN). This whole-ocean observation and monitoring network will be a first-in-class, large-scale system that measures changes in the state of the ocean as a result of the changing climate and human actions and will support better understanding and predictions of changes to the ocean's health and associated global climate impacts. The OVSN concept includes monitoring of ocean twilight zone processes as well as carbon flux measurements throughout the ocean water column.

Global monitoring systems (measuring terrestrial, oceanic and atmospheric parameters) are urgently needed to consistently monitor changing global and regional carbon budgets. These monitoring systems must measure trends and variations and reduce uncertainties towards the goal of establishing a robust capacity to 'Monitor, Report and Verify (MRV)' the outcomes of climate policies.[41] Towards this end, the OVSN, as an oceanic "network of things" targeting scientific and societal drivers, is ambitiously envisioned as an array of interconnected platforms, such as moorings stacked with state-of-the-art instrumentation, roaming gliders and other autonomous vehicles operating in the ocean and atmosphere, floats, and other instruments measuring 3-dimensional field variables (carbon, nutrients, eDNA, microbial ecosystem function, physical, chemical, and particulate properties, etc.).

This comprehensive network will continuously measure needed variables from the ocean-atmosphere surface through the water column and down into the seabed, and over multidecadal time scales. As such, the OVSN will incorporate the very latest in technological achievement and will also drive the ocean innovation economy to develop new instrumentation and approaches not yet invented. Ultimately, the goal is to greatly enhance the capability of the global ocean observing system through both advancing understanding and observing technologies.

OCEANS AND CLIMATE TALKS

The United Nations began to convene global climate talks in 1990, including many countries at various stages of development, with different socio-economic priorities and wide-ranging interests. Beginning with the adoption of the UN Framework Convention on Climate Change in 1992 to the most recent adoption of the Global Climate Pact in 2021, the UN has brought the world community ever closer to sharing the common goal of limiting global warming to 1.5C degrees. Even with significant actions taken to limit emissions, atmospheric GHG levels continue to rise. Conspicuously absent from the majority of climate talks is the central role that the ocean plays in stabilizing the global climate system through natural processes and the potential for the ocean to provide mitigation and adaptation solutions.

An exciting new movement towards recognizing the ocean's role in climate resulted in the UN's launch of the Ocean and Climate Change Dialogue in December 2020. This open dialogue collected views on how to address ocean-related mitigation and adaptation strategies which demonstrated the nexus between ocean, climate and biodiversity regimes. This focused attention, beginning at COP25, was carried forward to COP26 in Glasgow where the Dialogue was institutionalized to seek input and help refine the policies to be considered in future climate talks.

A review of the submissions to the first Dialogue revealed the "dire necessity to implement strong stewardship and good governance of the blue planet in a disrupted climate using cooperative and concrete actions."[42] A modest beginning was made with the acknowledgment of "the importance of ensuring the integrity of all ecosystems, including forests, <u>the ocean</u> and the cryosphere ..." in the preamble of the Global Climate Pact adopted in November 2021. Additionally, the Pact explicitly recognizes that marine ecosystems are important "carbon sinks" and therefore it is important to protect, conserve, and restore both terrestrial and marine ecosystems towards the goal of reducing GHG emissions. This COP heralded a new milestone for recognition of the critical role the ocean plays in our global climate.

On the margins of COP26, a declaration titled "Ocean for Climate" was endorsed by more than 100 civil society organizations (e.g. NGOs, scientists, companies and international organizations). The introduction to this declaration envisions the future we need for the ocean as follows: "It is the year 2050. The Ocean is thriving, and marine life is abundant. All marine ecosystems have recovered, dead zones have disappeared, fisheries are sustainably managed, aquaculture has grown quickly and sustainably, coastal and marine habitats are restored, and a massive loss of ocean life has been averted." This vision speaks to how degraded the ocean is today and that we have both the opportunity and obligation to take action now to avert more substantial harm to our habitable earth. This is pertinent to the ocean twilight zone, but applies to far more than that. The ocean twilight zone is one of the least impacted ecosystems in the ocean because of its depth range, which requires expensive efforts to harvest resources from it. Eventually, one can expect that technological barriers will be removed so that it becomes efficient to extract resources from the deep sea—so time is of the essence to expand scientific knowledge and develop science-based management policies for sustainable use of this vast ecosystem.

As of 2021, the UN is considering a global goal of protecting 30% of the world's ocean by 2030. With more than 70 nations signing on to this plan, the question of which areas should be prioritized for protection (or included in this 30%) will be debated over the next decade. As these discussions unfold, any improvements or clarity in our understanding of the twilight zone will help to shape policies that emerge by providing a firm scientific—rather than political—basis for decision-making.

By providing crucial information on the ocean twilight zone's scientific processes and role in climate, emerging scientific knowledge will support the Glasgow Climate Pact's goals of ensuring the integrity of ocean ecosystems and protecting biodiversity when taking action to address climate change. This is an essential step towards advancing the UN Sustainable Development Goals for the benefit of present and future generations.

The year 2022 will be pivotal in setting the stage for international discussions on ocean, climate and biodiversity. These include not only the processes set underway with the Paris Agreement on Climate Change and the Glasgow Climate Pact and the next iteration of it at Sharm-El Sheik where COP27 will be held, but also at the scheduled review of SDG 14. Other ocean policy milestones in 2022 include the potential adoption of the Post-2020 Global Biodiversity Framework at the High-Level Segment of the Convention on Biological Diversity (COP15) as well as UN-sponsored negotiations leading to the adoption of a treaty on biodiversity beyond national jurisdiction (BBNJ).

Other notable policy events scheduled include the One Planet Summit, focusing for the first time entirely on oceans to be held in Brest, France. This One Ocean Summit will focus on areas beyond the exclusive economic zone so that issues identified here, climate-ocean-biodiversity, are given their due, as it recognizes the ocean as a global public good. The seventh Our Ocean Conference to take place in Palau has identified ocean solutions for climate change as a priority topic. Both of these conferences will lead and feed into the UN Decade of Ocean Science for Sustainable Development conference appropriately called "Save Our Ocean, Protect Our Future."

The time is ripe for finding answers to many of the questions raised in this report so that the role of the ocean twilight zone and its potential contributions to stabilizing the global climate system will advance the way forward on how the global community can create a future that fosters strong stewardship and good governance of the blue planet.

URGENCY FOR ACTION

It is clear today that the ocean plays a massive role in global climate. Both as a sink for carbon and thermal energy, it acts as a buffer on the effects of human-emitted greenhouse gases—yet its ability to do so may hit an irreversible tipping point if emissions continue to climb.

The marine life within the ocean twilight zone is critical for its ability to keep climate in check. The vast amount of biomass it holds transports up to 6 billion metric tons of carbon annually from the surface layer down into the deep ocean. Once there, it potentially stays out of the atmosphere for millennia,[43] and in some cases, is deposited on the ocean floor indefinitely. Despite this essential knowledge, however, scientists do not yet fully understand what will happen if the twilight zone ecology is disrupted by human activity.

Worrisomely, the carbon sequestering efficiency of the ocean twilight zone is being threatened by the impacts of climate change: oceans that are continually warming and acidifying. These fundamental changes to the oceans will have profound impacts on the biological processes throughout the water column. Considering that trillions of twilight zone organisms migrate up to the surface each night to feed, climate-related changes affecting surface plankton and other primary producers will directly impact the wellbeing of deeper-dwelling species that rely on them for sustenance.

Warming climate is not the only threat to the twilight zone, however; the need to feed a rapidly-growing human population may also create a direct threat to twilight zone organisms. Estimates of up to 15 billion metric tons of biomass contained in the zone is an attractive target for future commercial fishing, which may seek to use mesopelagic organisms for fish meal and fish oil. Although these operations could be a viable way to produce nutrients for farmed fish, and by extension, increase the amount of protein available for human consumption, it is entirely unclear how large-scale fishing activity could affect the mesopelagic zone, or what unexpected consequences that disruption might have. If major commercial exploitation does occur, it could have a negative impact on existing fisheries (especially in species like tuna and swordfish, which feed on animals in the twilight zone). Harvesting mesopelagic species may also hinder the biological carbon pump's ability to move carbon from the surface into deep water, potentially resulting in further changes to global climate.

The need to understand the biological, physical, and chemical processes that take place in the ocean twilight zone has never been more urgent to humankind. This is not simply an academic exercise: it is a means of grasping and understanding the existential threats that could occur if humans alter an ecosystem that has existed in delicate balance for hundreds of thousands of years. Increasing our knowledge of how the twilight zone moves carbon—and how that transport may change in the future—will help to predict future climate, develop appropriate ocean and climate policies, inform ocean

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conservation efforts, and support sustainable ocean-based climate solutions. In short, increasing our scientific understanding of the ocean twilight zone is essential to stabilize greenhouse gas concentrations in the atmosphere, to prevent dangerous human interference with the climate system, and to limit global warming to well below 2 degrees Celsius, compared to pre-industrial levels.

We are effectively in the midst of a planetary-scale experiment: for the past few centuries, an exponential increase in human-caused emissions has been reshaping the global carbon cycle, changing Earth's climate, ocean chemistry and other natural systems. In terms of scale and significance, this "experiment" represents the largest transformation of natural systems ever experienced in modern times. The concept of *intergenerational justice* gives strength to the argument that there is an urgency in advancing scientific knowledge of the ocean twilight zone. In this context, the idea is that the present generation has the duty and responsibility to take proactive measures towards ensuring a habitable Earth for future generations. Knowledge must inform policy development. The policies shaped today to stabilize our climate and ensure sustainable use of the ocean twilight zone will set the course for generations to come.

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GLOSSARY

Anthropogenic: (Environmental change) caused or influenced by humans

Biodiversity: Variety of life

Biogeochemical: Process of transferring substances between living systems and the environment

Biological Carbon Pump: Biologically driven sequestration of carbon

Biomass: Total mass of organisms by volume

Bristlemouth Fish: Abundant family of mesopelagic marine fish

Carbon Dioxide Capture Technology: Technology used to capture CO_2 for subsequent long term storage

Carbon Sequestration: Natural or artificial process of storing CO_2 away from the atmosphere

Carbon Sink: Anything that absorbs more carbon from the atmosphere than it releases

COP26: United Nations Climate Change Conference of the parties held in Glasgow, 2021

Deep Scattering Layer: Schools of marine organisms dense enough to create a SONAR echo

DIC: Dissolved Inorganic Carbon - Inorganic carbon species (carbon dioxide, carbonic acid, bicarbonate and carbonate) dissolved in solution

DOC: Dissolved Organic Carbon – Generally resulting from decomposition processes from dead organic matter including plants and animals. DOC is operationally defined as organic matter which can pass through a filter with a pore size typically between 0.22 and 0.7 micrometers

DVM: Diel Vertical Migration - the synchronized, daily cycle of zooplankton and fish moving up and down in the water column

Ecosystem Services: Benefits to Earth's natural processes and humans from ecosystems

eDNA: Environmental DNA—Genetic material resident in the environment or leftover from organisms

Environmental Impact Assessment: Evaluating environmental impacts of a proposed project

Food Webs: Assemblage of all food chains in a single ecosystem

GESAMP: Group of Experts on the Scientific Aspects of Marine Environmental Protection - a group of independent scientific experts that provides advice to the UN system on scientific aspects of marine environmental protection.

GHG: Green House Gases – heat trapping gases in the atmosphere

Gigatonne: One billion metric tons

Gravitational Pump: Gravity acts to sink clumps of marine organic matter

Greenhouse Effect: Certain gases in Earth's atmosphere trap the Sun's heat

Inorganic Carbon: Carbon within ores and minerals

IPCC: Intergovernmental Panel on Climate Change. Comprised of 195 member countries, the IPCC prepares comprehensive Assessment Reports about the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place.

Marine Carbon Cycle: Carbon exchange between ocean, atmosphere, seafloor, etc.

Marine Protected Area: A park or protective measures implemented in marine regions

Marine Snow: Clumps of dead plankton, bacteria, fecal pellets, etc. rich in organic carbon

Mesopelagic: The ocean zone just below the surface zone from about 100-1000m depth

Micronekton: Swimming organisms in sizes from plankton (< 2 cm) to larger nekton (> 10 cm)

Migrant Pump: Ocean Twilight Zone organisms actively moving carbon into the deep ocean

Mixing Pump: Waves and turbulence move organic carbon particles deeper into the sea

MRV: Monitoring, Reporting, and Verification – measures which countries take to collect data on emissions, mitigation actions and support

NDC: Nationally Determined Contributions – efforts by countries to mitigate climate change

NET: Negative Emissions Technologies – removing Greenhouse gases from the atmosphere

Net Primary Productivity: CO_2 taken in by plants during photosynthesis minus CO_2 released from respiration

Ocean Acidification: The decrease in pH of seawater over time, trending towards acidity

Ocean Twilight Zone: Common name for the ocean mesopelagic zone

Organic Carbon: The form of carbon found in all plants and animals and their waste products

OVSN: Ocean Vital Signs Network – a Woods Hole Oceanographic Institution project

Petagram: One billion metric tons (equivalent measure to a gigatonne)

Photosynthesis: The process by which green plants, phytoplankton and some other organisms use sunlight to synthesize foods from carbon dioxide and water

Phytoplankton: Autotrophic (self-feeding using photosynthesis) plankton forming the base of the oceanic food web

PIC: Particulate Inorganic Carbon - PIC is mostly comprised of calcium carbonate, CaCO3, particularly in the form of calcite, but also in the form of aragonite. PIC is sometimes referred to as suspended inorganic carbon

Plankton: Small, diverse marine organisms that drift with tides and currents

POC: Particulate Organic Carbon - Generally resulting from decomposition processes from dead organic matter including plants and animals. POC is operationally defined as organic matter which can not pass through a filter with a pore size smaller than 0.7 micrometers

PPM: Parts Per Million. A common measurement for the mass of a chemical or contaminate per unit volume of water.

Solubility: Many gases dissolve in seawater such as oxygen, nitrogen and carbon dioxide

Solubility Pump: CO_2 is absorbed into the ocean and pushed deep by ocean circulation

Sustainability: Use of natural resources without causing a long-term decline of biological diversity or other valuable services that the ecology provides.

UNFCCC: The United Nations Framework Convention on Climate Change was established in 1994 to stabilize greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system."

Zooplankton: Animal constituent of plankton composed of small crustaceans and fish larvae

APPENDIX A. PRIMER ON CARBON, CARBON DIOXIDE AND BLUE CARBON

Carbon Dioxide (CO_2) is a potent greenhouse gas (GHG) consisting of one part carbon and two parts oxygen. It is also one of the most important gases on Earth because plants (on both land and in the ocean) use it to produce carbohydrates, i.e. organic matter, in photosynthesis: a life-sustaining process. Scientists are able to distinguish between natural CO_2 molecules and CO_2 resulting from burning of fossil fuels since atoms from the two sources have different numbers of neutrons in their C nuclei (known as isotopes). Since 1800, human activity has nearly doubled the amount of CO_2 in the atmosphere, driving it to levels the planet has not experienced for at least two million years.[44]

Comingling of the terms carbon and carbon dioxide causes significant confusion and errors in the media and in climate reports and discussions. The atomic weight of carbon is 12 atomic mass units, while carbon dioxide is 44 (CO_2 includes two oxygen atoms that each weigh 16). To calculate the mass of C contained in a mass of CO_2, multiply the mass of CO_2 by the fraction 12/44. Therefore, given 3.7 tons of CO_2, it equates to only 1 ton of carbon.

CO_2 is an important component of Earth's global carbon cycle, the process in which carbon atoms move, in various forms, between the atmosphere, land, ocean, and lithosphere (solid crust, rocks and minerals). Most of the carbon on Earth is stored in rocks and sediments, a part of the geologic reservoir that operates on time scales on the order of hundreds of million years, while the remainder of global carbon is stored in the ocean, atmosphere, and in living organisms, which operate on shorter time periods of minutes to millennia.[45]

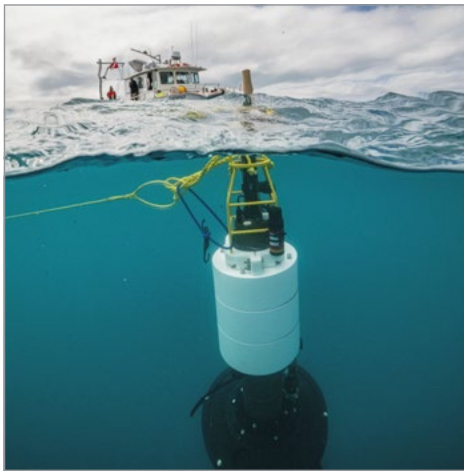
The quantity of carbon that is strongly influencing our changing climate only represents a tiny fraction of our planet's total carbon. More than 90% of carbon is stored in the interior of the Earth - in the crust, in the mantle and the core. A mere two-tenths of 1% of Earth's total carbon—about 43,500 billion tonnes—is estimated to lie above the planet's surface, in the ocean, on land, and in the atmosphere.

Blue carbon refers to the atmospheric carbon captured and stored by the ocean in various ecosystems and organisms. This activity mitigates the effects of climate change by storing carbon for long periods, often thousands of years or more. The tidal marshes, mangrove forests, and seagrasses found in coastal areas are most often considered blue carbon sinks, but marine organisms and biological processes in the open ocean can sequester even higher amounts of carbon.

Carbon and carbon dioxide are often measured in petagrams or gigatonnes. A petagram is a unit of mass equal to 1,000,000,000,000,000 grams (1×10^{15} grams), one quadrillion grams, one trillion kilograms, 2.2 trillion pounds, or one gigatonne. It is also worth noting the difference between a tonne in the Metric system and a Ton (short or long) in the Imperial measurement system. A short Ton (2,000 lb) is lighter than a metric tonne (1,000 kg). A long Ton (no longer in common use) is the heaviest of all (2,204.6 lb). For perspective, one gigatonne would roughly measure the weight of six million blue whales or twice the weight of all humans on Earth. A climate-related perspective is that the best estimate of the weight of ice from Greenland and the Antarctic that has melted into the ocean since the start of the 20th century is approximately 49,000 Gt.[46]

APPENDIX B.
INITIATIVES TO ADVANCE KNOWLEDGE OF THE OCEAN TWILIGHT ZONE

Large amounts of carbon move from the surface down through the twilight zone annually–but researchers are still not certain how life in the twilight zone affects that carbon's journey. Ocean scientists are working to expand our knowledge of the zone's place in the global carbon cycle using increasingly complex theoretical models, new tools and technologies, and multi-dimensional observation networks.



The WHOI-designed Twilight Zone Explorer (TZEx), is deployed in the ocean to gather data about marine snow, biological particles that float through the water column and serve the important role of transporting carbon from surface waters to the deep sea. Photo by Marine Imaging Technologies, LLC © Woods Hole Oceanographic Institution

WHOI's Ocean Twilight Zone Project

Researchers at Woods Hole Oceanographic Institution (WHOI) have embarked on a large-scale, comprehensive exploration designed to transform our understanding of the twilight zone, lay the groundwork for informed decision-making by regulatory organizations responsible for high seas, and capture the public's imagination to enhance ocean stewardship. The project comprises scientific discovery, technological innovation, and enhanced engagement with a wide range of stakeholders that includes scientific collaborators, the general public, and policy-makers worldwide. The Team is backed by WHOI's renowned leadership and expertise in ocean exploration and research and has the knowledge, experience, and technical capabilities to confront this enormous global challenge and help conserve a crucial part of the ocean for future generations.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

OCEAN TWILIGHT ZONE

Ocean Twilight Zone Observation Network

The Ocean Twilight Zone Observation Network, currently under development, will provide scientists with a comprehensive view of how carbon moves through the twilight zone. The network, which has been designed by a team based at Woods Hole Oceanographic Institution, will eventually cover a region of about 250,000 square kilometers (roughly 155,300 square miles) of the Northwest Atlantic Ocean. It is made up of sonar moorings, highly sensitive fish-tracking tags, and mobile submersible sensor systems, including a fleet of new MINION (MINiature IsOpycNal) floats. MINIONs, which are camera-laden devices that help to record the quantity and type of marine snow particles falling through the twilight zone, will help tease out the biological carbon pump's role in the global carbon cycle.

Together, this collection of instruments will give researchers around-the-clock data from the twilight zone over months or even years. Information collected using the Observation Network will help to improve estimates of the amount of carbon that moves through the twilight zone and could reveal how biological organisms affect that movement through their interactions and daily migrations to the surface. In the process, the network will help scientists understand how twilight zone organisms affect global climate—and provide unprecedented insight into a little-known, yet vitally important region of the ocean.

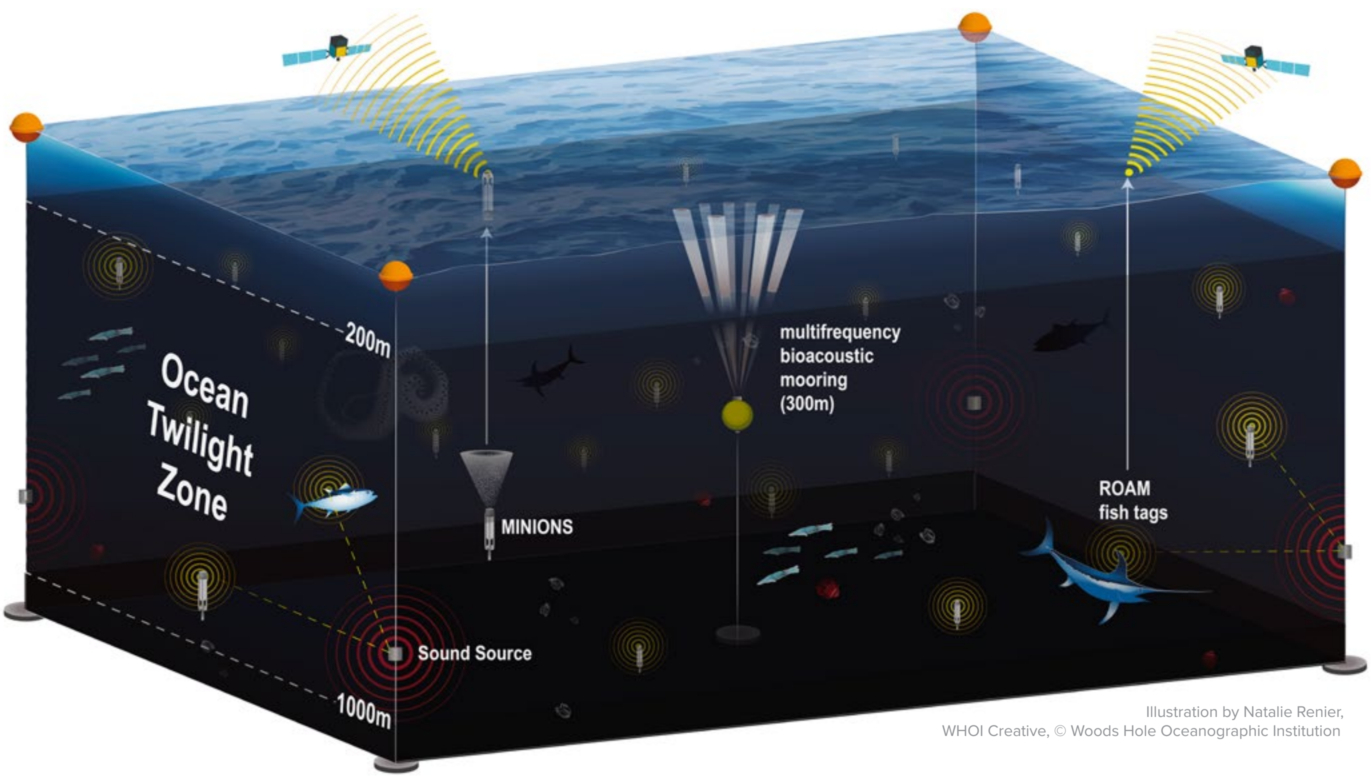


Illustration by Natalie Renier, WHOI Creative, © Woods Hole Oceanographic Institution

Joint Exploration of the Twilight Zone Ocean Network

The majority of the ocean twilight zone is in the open ocean, outside of coastal waters and national boundaries. For this reason, studying it requires collaborations that span academic disciplines and political borders. Since 2019, JETZON (the Joint Exploration of the Twilight Zone Ocean Network) has coordinated teams of international researchers at all levels—from graduate students to senior scientists leading large multinational projects—and has brought them together to answer long standing questions about the twilight zone. JETZON aims to provide new scientific understanding of potential stressors such as fishing, deep-sea mining and proposed carbon sequestration strategies on the twilight zone to inform international ocean and climate policy. In 2021, JETZON became one of the first twenty eight programs to be endorsed by the United Nations Decade of Ocean Science for Sustainable Development.

United Nations Decade of Ocean Science for Sustainable Development

The United Nations has proclaimed a Decade of Ocean Science for Sustainable Development (2021-2030) under the vision, "The science we need for the ocean we want." The "Decade" is supporting efforts to reverse the cycle of decline in ocean health and to provide a common framework for global ocean stakeholders to ensure that ocean science will support countries in creating improved conditions for sustainable development of the Ocean. JETZON is an endorsed Decade Programme and the Ocean Twilight Zone Project has applied to become an endorsed project. Many other Decade initiatives and endorsed programmes are designed to improve scientific understanding of the deep sea.

Integrated Assessment Models

Integrated Assessment Models (IAMs) are a powerful tool to test the economic repercussions of climate-related issues at the global or regional scale. Models like these take into account a wide range of elements, including shifts in energy production and consumption, global trade, public health crises, coastal storm damage, sea level rise, and other social/environmental impacts of changing climate. In doing so, they help to reveal the real-world monetary impact of carbon emissions.

Incorporating the twilight zone into these simulations will be critical. Since the zone has an outsized impact on global climate, advances in scientific knowledge of its waters will lead to more nuanced and accurate results from IAMs. The result of these improved simulations could inform new policy decisions as they're being made, and could provide a way to compare the costs of climate mitigation with the costs of climate-related damage (i.e. coastal erosion, infrastructure/property damage, public health, etc.).

Export Processes in the Ocean from Remote Sensing

One of the greatest challenges faced by oceanographers is quantifying how marine ecosystems affect Earth's carbon cycle—and by extension, its climate. The EXPORTS (EXport Processes in the Ocean from Remote Sensing) program is working to fill those knowledge gaps. Funded by NASA and the U.S. National Science Foundation, WHOI and other participating institutions are seeking to understand how carbon moves from the atmosphere into the surface ocean, and from the surface to deeper water. The group also seeks to understand what the ultimate fate of that carbon may be.

Through its work in the Pacific and Atlantic Oceans and the international collaborations it fosters, EXPORTS is advancing work in remote sensing and ecosystem modeling of the upper ocean and twilight zone, and is helping researchers examine relationships among the ecological, biogeochemical, and physical oceanographic processes that control carbon cycling in the ocean. In addition, EXPORTS supports a combination of ship-based data collection, traditional and robotic field sampling, and numerical modeling. The results of this work help researchers to understand the twilight zone's impact on climate, and will improve our knowledge of the Earth as an integrated system.

(From top) the R/V *Sarmiento de Gamboa*, the RSS *James Cook*, and the RSS *Discovery* rendezvous in the northeast Atlantic during a three-ship EXPORTS research cruise in spring 2021

Other Emergent Scientific Efforts

Scientific efforts to study the twilight zone are beginning to grow worldwide. Over the past decade, they have also increased in collaborative reach across national borders—yet these research projects have only just begun to unravel some of the zone's many complex natural processes. For this reason, Woods Hole Oceanographic Institution has spearheaded or joined wide-ranging collective endeavors that serve as a model for international collaboration in marine science, including efforts that are promoted by the UN Decade of Ocean Science for Sustainable Development. The JETZON website (jetzon.org) includes links to many of the research efforts being conducted worldwide to better understand the twilight zone's effects on global climate.

Representative of the incredible ocean twilight zone biodiversity.
Photo by Paul Caiger, © Woods Hole Oceanographic Institution

THE OCEAN TWILIGHT ZONE PROJECT

Combining science, innovative technology, and broad engagement to turn knowledge into action

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