

Shedding Light on Light in the Ocean

New research is illuminating an optically complex environment

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Light in the ocean is like light in no other place on Earth. It is a world that is visibly different from our familiar terrestrial world, and one that marine animals, plants, and microbes are adapted to in extraordinary ways. Light behaves very differently when it moves from air into water. It moves through the expansive depths of an ocean that is devoid of solid surfaces. These and other factors combine to create an environment that has no equivalent on land.

A scuba diver in the open ocean discovers she is immersed not only in water, but also in an ethereal blue light. Seawater absorbs light much more strongly than air does, but visible light is made up of a rainbow of different wavelengths, each perceived by us as a different color. Blue light penetrates farther into seawater (giving the ocean its distinctive color). At the same time seawater absorbs red, orange, and yellow wavelengths, removing these colors. Only a few meters below the sea surface, if our diver looked into a mirror, she would see that her red lips appeared black.

In calm weather, the diver can look upward to see the entire hemisphere of the sky compressed into a circle over her head—a phenomenon called Snell's window, caused by the bending of light as it enters water. Rough weather and waves shatter this window. The waves act like lenses to focus light, creating a scintillat-

ing visual field whose brightness increases and decreases by a factor of a hundred as each wave passes by, making it impossible for eyes to adjust.

If our diver wore ultraviolet (UV)-viewing goggles, almost half the light she



Larry Madin, WHOI

A scuba diver in the open water is immersed in clear, pure blue light. Water strongly absorbs red, orange, and yellow light, while blue light penetrates into the depths.

would see looking down and horizontally would be UV. Light passing through water also becomes polarized, which means its wave motion vibrates in only one direction, or plane. (This also happens to the light reflected as glare from the sea surface or a wet road.) If our diver wore sunglasses that blocked vertically polarized light and looked to her side, her view would be dark; but if she looked up or down, her view would be full of light. The polarized sunglasses would block light vibrating in the horizontal plane, while allowing light vibrating in the vertical plane to pass through.

Light frames life

In many ways, light permeates and creates the environment that ocean organisms experience. The same is true on land—though we often take light for granted. We see light as background, when it actually sets the stage and dictates our view of the world. As sure as day follows night and the sun makes plants grow, light frames our existence. So it is, too, in the ocean, where animals and plants are bathed in different kinds of light coming from all directions, in a way we land-dwellers never experience. Some animals possess visual systems that see ultraviolet and polarized light (which people cannot) and have clever strategies to avoid detection in an environment where one can be seen from every angle and there is nothing to hide behind. Even in the sunless depths, light still plays a crucial ecological role, with armadas of bioluminescent life making and using their own light.

Humans have had limited ability to ex-

plore the dimension of light in the ocean. Today, however, new technology promises to reveal how light operates in the ocean and how it creates a unique environment and assorted phenomena that ocean life is adapted to.

Wavelengths in the waves

When light hits a substance, it can do one of three things: it can be scattered, by hitting molecules of the substance and bouncing off in different directions; it can pass through the substance; or it can be absorbed by the substance—either wholly or in only some wavelengths. Much sunlight reflects off the ocean, but much also penetrates into it and is strongly absorbed

by seawater. Several hundred miles from shore, our diver sees extraordinarily clear and pure blue water because water in the open ocean has low concentrations of dissolved matter and particles, including phytoplankton. It does not scatter and absorb as much light as murkier coastal water does, and the light that remains is blue.

Nearer the coast, light penetrating seawater provides the energy to fuel vast photosynthetic hordes of microscopic marine plants—phytoplankton—which are an essential source of food and oxygen for the entire planet. Just below the surface, our diver will see green light, depending on how much phytoplankton is present. Water with high concentrations of phyto-

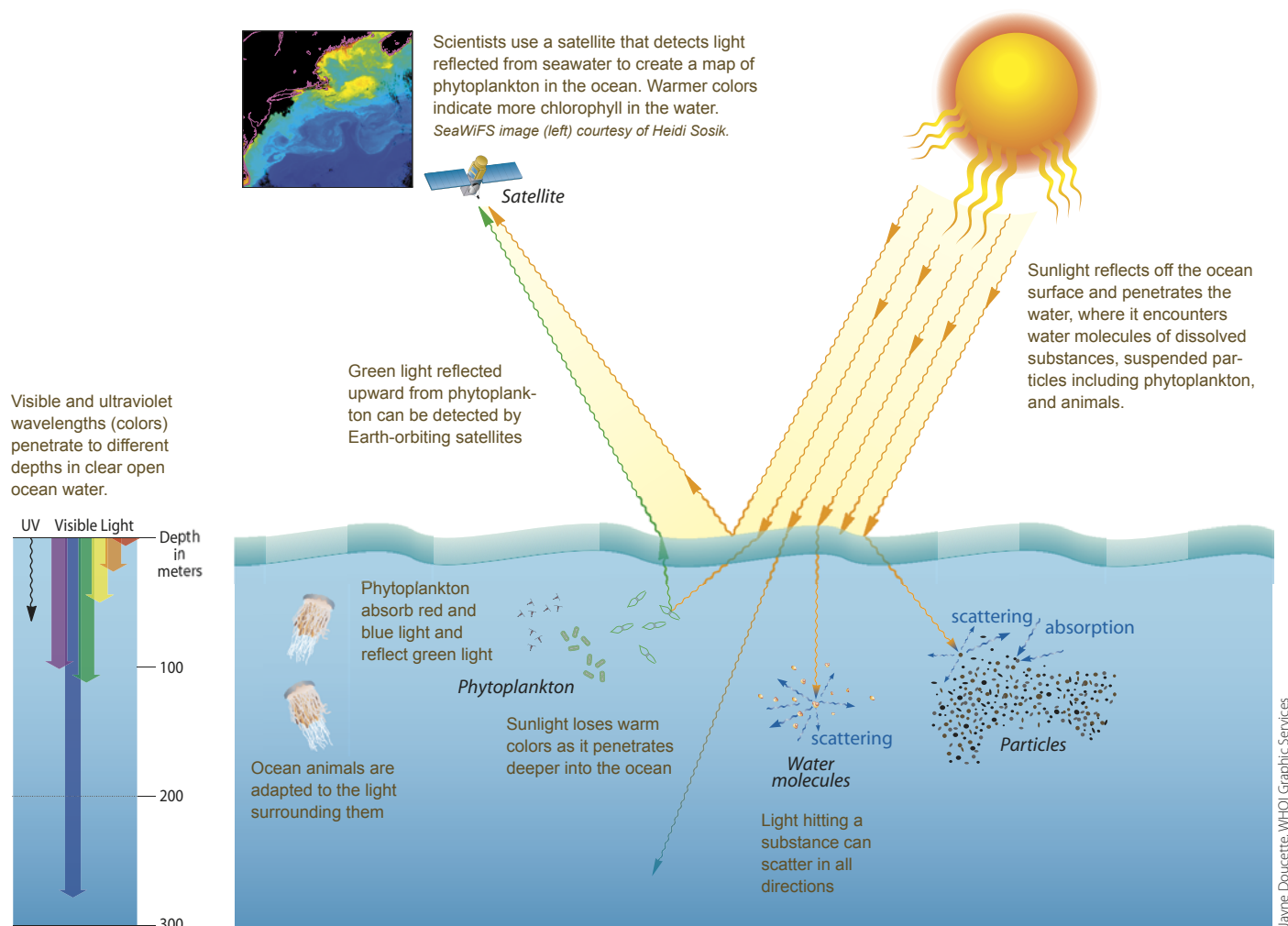
plankton is green and darker for the same reason that dense tropical forests are: Plant pigments absorb blue and red light and reflect green light, and the cells scatter the light more than pure water does. While the diver would not be able to detect microscopic phytoplankton cells, she would see their cumulative effect on the light in the ocean.

Providing the oxygen we breathe

Beyond their impact on light, marine phytoplankton also have enormous impact on our planet. Photosynthesis by these abundant cells produces roughly half the oxygen in our air.

Phytoplankton have evolved the abil-

Light in the Ocean



ity to use the blue and green light found in the ocean. If water were not relatively transparent to this light, aquatic photosynthesis would not be possible, and the ocean would be largely a dead zone. In addition, if coastal waters become less clear due to human activities, photosynthesis by phytoplankton may decrease.

Phytoplankton form the base of the prolific marine food chain, which ultimately also helps feed people and other terrestrial life. Throughout Earth's history, phytoplankton have also played an important role in regulating Earth's climate. They remove huge amounts of the greenhouse gas carbon dioxide from the atmosphere, turning it into organic matter via photosynthesis. Much of this organic carbon is consumed by animals in upper ocean waters. Some falls to the seafloor, as dead organisms or fecal pellets, where it is consumed or converted over time into oil and gas deposits.

The threat of UV radiation

Marine photosynthesis is confined to the tiny fraction of the ocean where sunlight penetrates—at most, the upper 200 meters. UV light also penetrates into this region, which may have increasingly profound consequences. UV radiation can cause damage to organisms on both land and sea. Recently, scientists have discovered that ultraviolet radiation can harm organisms deeper down than previously thought.

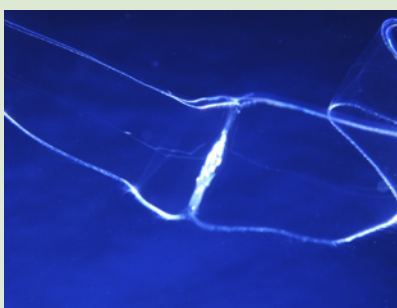
Decreasing ozone levels in the atmosphere, including the ozone hole over Antarctica, may exacerbate the problem, because ozone blocks UV radiation from reaching Earth. Higher levels of UV can kill phytoplankton, slow their growth, or disrupt the delicate balance of species that interact in ocean ecosystems.

Marine organisms have evolved ways to protect themselves from UV, including UV-absorbing pigments, the ability to repair DNA damaged by UV, and developing behavior to avoid UV by staying in deeper water. However, the recent ozone changes may be occurring too fast for

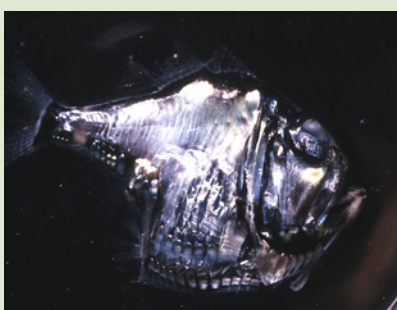
Adaptations to light, from surface to depths



The dark backs and light undersides of these near-surface fish help them match their environment in the open ocean. To a predator looking from above, their dark backs seem to blend into the dark depths. From the side, their lighter sides blend with the sunlit water.



Many open ocean animals use invisibility to hide in plain view. Adapted to limitless, featureless blue surroundings, this planktonic ctenophore, Cestum, lives near the ocean surface. The complete transparency of its body makes it almost impossible to see against the open ocean waters.



The hatchet fish is well prepared for the midwater ocean's light levels. Bright silver sides reflect whatever light surrounds it. Long, tubular eyes capture and detect low light levels. Living at depths from 200 to 1000 meters, it has ventral (underside) light organs that can produce bioluminescence to match light coming from above, making it less visible from below.



With enormous upward-looking eyes that fill half its otherwise transparent body, the deep-living shrimplike amphipod Cystisoma is well-suited to its dim world. It needs such large eyes to detect the little light available in its midwater environment (800 meters), and red eyes, at that depth, look black—and invisible.



Atolla is a jellyfish common from mid-water, about 500 meters deep—where there is still a small amount of sunlight, to bathyal depths of 4500 meters—far below the limit of sunlight's penetration. Where there is light, its red color looks black, making it hard to see. It also produces brilliant bioluminescence, possibly to frighten predators.

Images courtesy of Larry Madin/WHOI

organisms to adapt. Given the fundamental role of phytoplankton in Earth's biology, chemistry, and climate, these changes may affect us all.

Into the darker depths

As our diver continues to descend only a few more meters, she begins to go from day to night. She can see blue light to her sides, and white light above, but below her the view is dark. As she moves downward, the UV, green, and violet wavelengths disappear, and the light becomes an intense, almost laser-like, pure blue. At 200 meters deep, the diver would cross from the surface realm (called the epipelagic zone), where there is enough sunlight for photosynthesis, to the twilight realm (called the mesopelagic zone), where enough sunlight penetrates for vision, but not for photosynthesis.

By now, our descending diver would notice nearly continuous blue flashes around her—bioluminescent light produced by animals in the midwater zone, in response to the disturbance in the water that she caused. Below 850 meters, though, the diver would no longer be able to see anything, even looking up. Human eyes aren't sensitive enough to detect the minute amounts of sunlight that haven't been absorbed by the water. At 1,000 meters, even the most visually sensitive deep-sea animals can no longer see the sun. The region below this is known as the aphotic (no-light) zone, but this is only true for sunlight, as bioluminescence is common.

Predators—using light to hunt

Not surprisingly, aquatic animals possess visual systems that are specially adapted to the nature and properties of light underwater. Animals living near well-lit surface regions have eyes similar to terrestrial species. They have color vision, since light near the surface still has color.

Many also have UV vision, which advantageously extends their range of vision. Many animals contain compounds in their tissues that protect them against UV radiation by scattering, reflecting, or ab-



Courtesy of Tom Cronin

The advantage of UV vision shows in reef views in visible (left) and ultraviolet (right) light. In UV light, the fish are in much higher contrast to the background.



Courtesy of Nadav Shashar

Bottom: Prey species like the copepod (Labidocera), are nearly transparent in visible light (left), but are brightly visible when photographed in polarized light (right), or to a predator that can see polarization of light.

sorbing UV light. This makes the animals appear dark and silhouetted against an otherwise bright background of UV light. With UV vision, animals can see animals that are transparent in visible light.

Some ocean animals, such as shrimp and squid, can even see the polarization of underwater light—due to a special geometric arrangement of their retinas. With this ability, they can actually navigate by the skylight polarization pattern, or detect otherwise transparent, or silvery-scaled prey by seeing its effect on the polarization of light.

In deeper, mesopelagic regions with less light, the animals often have bizarre adaptations to increase their visual sensitivity. They see in extremely low light levels, though at the expense of acuity, with a reduced ability to detect rapid movements. Long, tubular, telescope eyes in fish, or

enormous crustacean eyes that fill the animal's entire head capture as much light as possible.

Prey—using light to camouflage

But seeing is only part of the equation. Ocean organisms' visual adaptations are matched by clever strategies to avoid being seen in an open ocean where it is difficult to hide. Some color themselves to match the background water. Others have mirrored sides, because a mirror in the ocean only reflects more of the ocean, and so is invisible.

Still others camouflage themselves with light, hiding their silhouettes with light-producing organs on their downward-facing surfaces that mimic the surrounding illumination. Many are simply transparent, matching their background in all situations.

Finally, some use light and dark for disguise. They hide in the depths during the day, rising to feed at night, or they stay near the surface, hiding in the glittering background of the lensing waves.

Instruments to measure light

To study light in the sea, scientists use a wide range of instruments—submerged in the depths and sent into space. Submersible radiometers, or light meters, measure ultraviolet and visible light and detect extremely low light levels in the deep sea. They numerically describe the shape of the light field in the ocean and measure how light is absorbed and scattered in water over small spatial scales. They can be lowered from ships, placed on submersible vehicles, or even carried by scuba divers to investigate the optical environment of specific areas or depths.

One of the most exciting advances in oceanography has been the developing ability to measure changing color over wide swaths of the ocean, using Earth-orbiting satellites that carry spectral radiometers that measure light reflected from the surface layer of the ocean. These color changes indicate changes in the global distribution of phytoplankton. For the first time, oceanographers can see how phytoplankton populations bloom, collapse, and change over time in any area, and these satellite views have revolutionized how we think about the upper ocean.

A bright future

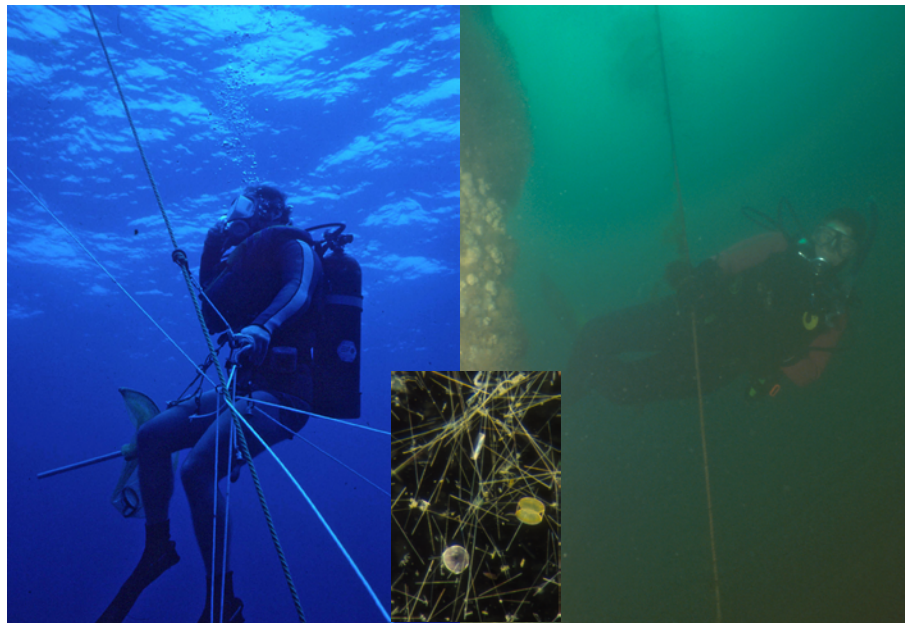
Despite continually improving satellite data, optical oceanographers still have too few observations. Satellites view only the upper few meters of the water. With underwater instruments, we can sample only relatively few specific places and times in the ocean. What's lacking is a way to visualize the entire ocean—surface to depths and across the globe.

Computer models offer a way to approach this deficit. Combining available observations with new, accurate computer models that simulate how light behaves and propagates through the ocean has led

to insights on satellite-based ocean color measurements, global phytoplankton productivity, and how marine animals use light and camouflage.

The door is now open to answering

questions about the operation of light in the ocean, and its role in the lives of marine phytoplankton and animals. We are gaining new understanding of this heretofore shadowy—but not lightless—realm.



Left photo and inset by Larry Madin, right photo by Terry Roux, WHOI.

DIVING INTO DIFFERENT WORLDS: Open ocean water (left) contains few particles and absorbs warm colors, so blue light penetrates far into the clear distance. Near the coast, high nutrient levels allow dense growth of phytoplankton (center), making the water appear green and darker (right). Forests appear dark and green for the same reason—plant pigments absorb red and blue wavelengths of light, and reflect remaining green light.



Sönke Johnsen entered biology with backgrounds in math, physics, and art and has since used all three fields to investigate the visual ecology of oceanic zooplankton. After a frustrating graduate career, in which he studied the vision and behavior of animals with neither eyes nor brains, he completed postdoctoral fellowships at Harbor Branch Oceanographic Institution and WHOI. After a year as an assistant scientist at WHOI, he accepted a position in the Biology Department at Duke University. He is interested in all aspects of vision in oceanic species, with a particular

emphasis on strategies for camouflage. The camouflage research has involved investigations into UV vision, whole-body transparency, cryptic coloration, and counterillumination using techniques ranging from blue water diving to protein biochemistry to Monte Carlo modeling of photon trajectories. He gives numerous talks to the general public and his work has been featured in newspapers, magazines and a John Updike poem*. (*http://www.swarthmore.edu/NatSci/SigmaXi/archive/SX_johnsen_announcement.pdf)



Heidi Sosik received bachelor and master of science degrees in Civil and Environmental Engineering from MIT in 1988 and a doctorate in Oceanography from Scripps Institution of Oceanography in 1993. She joined the Woods Hole Oceanographic Institution as a Postdoctoral Scholar in 1993 and is now an Associate Scientist in the Biology Department. Her research interests focus on phytoplankton ecology and factors that influence light in the marine environment. She received a Presidential Early Career Award for Scientists and Engineers in 1996 and is currently a joint Fellow of WHOI's Ocean Life Institute and Coastal Ocean Institute. "Never a dull moment" is an apt description of life for Heidi, whose family—one husband, three kids, two dogs, and a cat—keep her keel even and her sails full through the ups and downs of a career as an oceanographer.