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On a Collision Course: Ocean Plankton and Climate Change

CHERYL LYN DYBAS

Plankton are showing the effects of a warming climate as marine populations worldwide experience a regime shift caused by climate change. In northern oceans, biogeographical boundaries are shifting northward as warm-water species displace cold-water species, causing trophic cascades. Ocean acidification is accelerating and threatening the long-term survival of many marine species.

For thousands upon thousands
of years
The sunlight and the sea and the
masterless winds
Have held tryst together.
Llewelyn Powys

Once a month, on the darkest nights near the new moon, otherworldly beings emerge from Pacific Ocean depths and drift onto the beaches of Hawaii. Hundreds, sometimes thousands, of these quivering masses of jelly float in with the night tide 8 to 11 days after a full moon. Near shore, time grows short to complete their mission: to reproduce, leaving behind miniature versions of themselves fastened with a gluey substance to reefs and rocks in the shallows.

Box jellyfish, the marauders are called. "They come in each month with unbelievably precise timing," says marine scientist Jerry Crow of Honolulu's Waikiki Aquarium, "and in a frenzy to reach their destination."

Crow and colleagues are studying Hawaii's box jellies, tracking patterns of abundance of the jellyfish and how those might be related to changing environmental conditions. "Over the past few decades," says Crow, "more and more box jellies have been found in the waters around Hawaii. Their numbers reached a peak from about 1998 to 2001, then began to decline. But box jellies were initially found only on the southern, or windward, coast of Oahu. Now they're on both the western and northern coastlines, too. No one knows for sure why."

This unexplained pattern, says Crow, is why it's essential to conduct long-term studies on the interactions of plankton and ocean ecosystems.

Populations of jellyfish—members of the ocean's floating cadre of animals and plants called plankton—are exploding in seas around the world, scientists say, raising concerns about the health of marine ecosystems. Off the coast of France, aggregations of jellyfish have sunk 500-pound fishing nets. In Japan, jellies have clogged the water intakes of nuclear power plants.

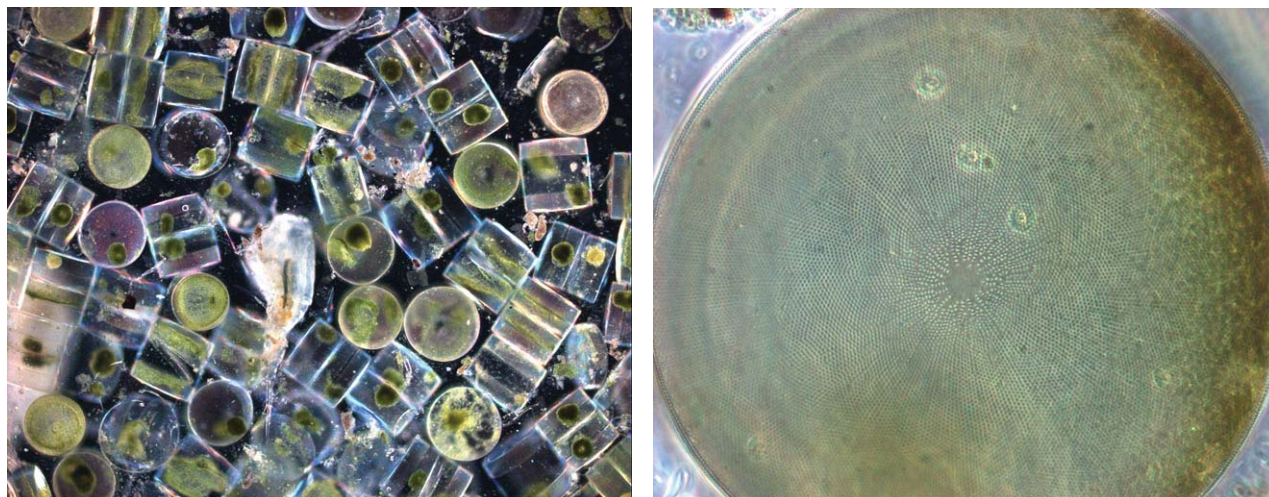
One Gulf of Mexico shrimp boat captain says that at certain times of the year in the gulf, "you can almost walk on water—on jellyfish. What the heck is going on?"

No longer, it seems, do the sunlight, the sea, and the masterless winds hold tryst together. Or perhaps the tryst they hold is one radically altered from what it once was.

Plankton populations and climate change

The leading perpetrator on the list of suspects (which includes overfishing and nutrient pollution) is global climate change. Biological oceanographer Christopher Lynam of the University of St. Andrews in Fife, Scotland, attributes increasing jellyfish abundance in marine ecosystems to regime shifts associated with climate change.

The term "regime shift" describes widespread and prolonged climate-linked changes in biological systems. Such shifts had occurred in the northern Pacific Ocean by the 1970s and in the North Sea by the mid-1980s. In the



This well-known species of diatom, *Coscinodiscus wailesii* (sizes range from 280 to 500 micrometers in diameter), is often so abundant that it clogs fishermen's nets in places like the North Sea. It is one of the species of phytoplankton at the center of the ocean's food web and among the life forms most affected by climate change. Micrographs courtesy of Sir Alister Hardy Foundation for Ocean Science.

North Sea, a change from cold-water to warm-water species happened as the ocean's biogeographical boundary along Europe's continental shelf moved north.

In an article in the journal *Limnology and Oceanography* (May 2004), Lynam and coauthors discuss the effect of this regime shift on the abundance of North Sea jellyfish. "It appears that variation in the abundance of jellyfish is driven by changes in climate," says Lynam.

The evidence for climate change effects on plankton abundance and community structure over recent decades is strong. From the smallest—tiny shrimp-like krill, copepods, and microscopic cocolithophores—to the largest—gelatinous medusae and siphonophores—plankton are showing the effects of a warming climate.

The term *plankton* comes from the Greek word "planktos," to drift or to wander. In aquatic science, it describes plants (phytoplankton) and animals (zooplankton) that passively float along currents. Plankton can swim up and down in the water column under their own power but otherwise can't move unless they hitch a ride on a current. Ubiquitous in the seas, plankton, whether microscopic or macroscopic, are integral to the functioning of a range of ocean cycles. Some recycle nutrients from the surface

to the depths and back again, while others are fuel for fish and whales on their long-distance migrations.

"Oceans cover almost three-quarters of the surface of the Earth, so we need to understand how changing climate is affecting marine biota," says scientist Graeme Hays of the University of Wales. "Plankton are at the center of this concern." These effects, Hays believes, "may have widespread economic as well as ecological implications." Larger ocean animals and plants, which depend on plankton at the base of their food webs, "have a huge socioeconomic value," he says, estimated at \$21 trillion per year, including food production, recreation, and other ecosystem services.

Unlike marine species such as fish and intertidal organisms, few members of the plankton are commercially exploited. "Therefore, any long-term changes [in their populations] likely can be attributed to climate change," wrote Hays and colleagues in the journal *Trends in Ecology and Evolution* (June 2005). And since most plankton are short-lived, plankton population size isn't influenced by persistence of individuals from previous years. "There's a tight coupling between climate change and plankton dynamics," says Hays. "Because they're free-floating and can respond easily to changes in temperature and ocean currents, plankton

can easily expand and contract their ranges."

When these populations crash, recovery is slow. Plankton ecosystems in Earth's oceans took 3 million years to fully recover after the mass extinction event 65 million years ago, according to scientists Helen Coxall and Steve D'Hondt of the University of Rhode Island Graduate School of Oceanography and James Zachos of the University of California—Santa Cruz. In a paper published in the April, 2006, issue of the journal *Geology*, the researchers state: "The three-million-year delay in organic [carbon] flux and planktic foraminifer evolutionary recovery attests to the far-reaching effects of extinction in the marine realm, and implies that the time required to repair food chains and reestablish an integrated ecosystem is extremely long (millions of years)."

Trophic cascade

While jellyfish populations in the North Sea are increasing in response to human-caused climate change, seabirds there are suffering declines as a result of global warming. On the isle of Shetland off the coast of Scotland, there once were more than 1200 nesting pairs of guillemots. In recent summers, there were none. The birds returned to their cliffside nesting grounds, but nests remained empty.



Planktonic foraminifera are small, amoeba-like organisms that live inside shells, or “tests,” such as those seen here. Most forams live near the surface of the world’s seas and, though small (on the order of a few tenths of a millimeter), are very abundant. Over the centuries, their shells have been preserved as fossils in seafloor sediments, providing a long-term perspective on recent changes.
Photograph: © 2002 David Field.

Elsewhere on Shetland, more than 20,000 nests of another seabird, the arctic tern, were vacant. And a few miles away, on the island of Foula, the largest colony in the world of great skuas had only a few chicks. Ornithologists say they have never seen such reproductive failure. It has resulted in the loss of hundreds of thousands of the world’s seabirds.

The adults of all these species, it appears, are starved for food. They subsist on fish called sandeels, small, silvery fish usually abundant in the nearby waters of the North Sea. But now the sandeels have disappeared, and little other prey exists. The birds are forced to fly farther and farther seaward to find food. Most have not been able to locate enough sandeels or other fish to eat to have the energy to produce eggs. Sandeels are disappearing because the cold-water plankton the fish eat have moved north. Historically icy waters between England and Scandinavia have become too warm for the plankton to survive there.

“Climate change is heating Earth’s northernmost waters much faster than it is those near the equator,” says Hays.

Some species of plankton have shifted northward in response, while warm-water and subtropical fish like squid and red mullet are now seen in formerly frigid seas. As the North Sea has warmed, seabird populations on islands off Scotland have decreased by as much as 70 percent. Many commercial fisheries, especially those in Denmark that depend on sandeels, are in financial distress. This ecological crash, which spreads through predator–prey relationships, is known as a trophic cascade.

“Sea-surface warming in the northeast Atlantic Ocean has resulted in increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions,” says scientist Anthony Richardson of the Sir Alister Hardy Foundation for Ocean Science in Plymouth, United Kingdom. “This impact transfers up the food web from phytoplankton to zooplankton and beyond. Future warming is therefore likely to place additional stress on already depleted fish and mammal populations.”



Pteropods, or sea butterflies, are among the plankton most affected by increasing ocean acidity. The Limacina helicina pictured here (shell length is about two millimeters) was one of the 450 species sampled on a recent Census of Marine Life cruise in the Atlantic Ocean. An onboard sequencer enabled an international team of scientists, including Russ Hopcroft of the University of Alaska–Fairbanks, to uncover new genetic information on some 220 planktonic species.
Photograph: Russ Hopcroft.

Acidic oceans

As climate change accelerates, the world’s oceans are absorbing more carbon dioxide, increasing the acidity of ocean waters, which are slightly basic or alkaline in their natural state, and threatening the long-term survival of many marine species. Plankton with calcium carbonate skeletons, like foraminifera, can’t manufacture calcium carbonate in acidic waters.

At a symposium organized by the United Nations Educational, Scientific and Cultural Organization’s (UNESCO) Intergovernmental Oceanographic Commission (IOC) and the International Council for Science’s Committee on Ocean Research, researchers presented results showing that a lowering of ocean pH can disrupt marine food chains and alter ocean biogeochemistry. Christopher Sabine of the National Oceanic and Atmospheric Administration (NOAA) found that since 1800 the ocean has taken up about 120 billion metric tons of carbon generated by human activities. According to IOC estimates, some 20 million to 25 million metric tons of carbon dioxide are added to the oceans each day.

The uptake of carbon dioxide by the oceans reduces the concentration of this gas in the atmosphere and mitigates its impact on climate warming. Now, however, there is a growing concern about the price of this “service.” According to a 2004 UNESCO report, *Priorities for Research on the Ocean in a High-CO₂ World*, accumulating ocean carbon dioxide is leading to changes in ocean pH three times greater and 100 times faster than any the oceans have experienced.

The ocean forms carbonic acid with the carbon dioxide absorbed by seawater. At the current rate of carbonic acid formation, within a century, scientists believe, the surface of the Southern Ocean near Antarctica will be corrosive to the shells of floating snails called pteropods, an important link in the food web there.

The view from sea and sky

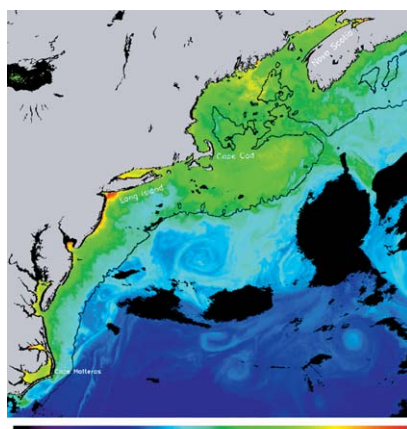
Decades ago, England’s Sir Alister Hardy realized that phytoplankton must be observed through the seasons to understand their population dynamics. “The

naturalist with a tow-net, if he can sample the plankton at different times of the year, will find contrasts between spring, summer, autumn and winter almost as striking as those in the vegetation on land.” There is not, however, “a simple and gradual increase in the plankton as spring advances into summer, followed by a gradual decline in the autumn,” Hardy believed. “Our naturalist with a tow-net will find some of the changes very puzzling at first sight.”

Hardy was among the first to realize that scientists lacked a comprehensive method of studying plankton. “Hitherto our knowledge of the density and distribution of plankton has been gained from samples taken at a number of stations within the area concerned,” he wrote in an article published in *Nature* (30 October 1926). “When, as on long cruises, the stations have to be twenty, fifty, or even a hundred or more miles apart, it may be doubted whether such samples are giving a true idea of the content of the water traversed.” Hardy felt the need for an instrument that, by giving a continuous record mile by mile, “would enable one to study and compare the uniformity or irregularity of planktonic life in different areas, to measure the size, varying density, and frequency of patches [of plankton], and to indicate more exactly than can be done with comparable tow-nettings whether any correlation exists between different species.”

Enter the continuous plankton recorder (CPR), invented by Hardy and still in use today. Towed over long transects of ocean, it collects plankton on a filter. In the world’s largest plankton survey, more than five million nautical miles in the north Atlantic Ocean have been sampled since 1931 using a CPR. Some 450 phytoplankton and zooplankton taxa have been found in each sample. “Much of our current understanding of the impacts of climate change on lower trophic levels comes from this survey,” says Hays. In addition to its use aboard a research vessel, a CPR can be used on a “ship of opportunity” such as a cruise ship or cargo vessel.

Richardson, Martin Edwards, and colleagues at the Sir Alister Hardy Foundation for Ocean Science carry on Hardy’s



Tracking plankton blooms from space and comparing them over time is giving scientists new insights into how climate change affects the distribution of plankton. This SeaWiFS image shows the concentration of phytoplankton in waters off the northeastern US coast, where productive, high-chlorophyll waters are shown in yellow and green and low-chlorophyll waters in deep blue (clouds are in black). The solid black line is the approximate outer boundary of the continental shelf. Graphic courtesy of Jim Yoder and NASA's SeaWiFS Project and Orbimage.

early work. They study phenology, the timing of recurring natural phenomena. Using long-term data on 66 plankton taxa during the period from 1958 to 2002, they investigated whether climate warming affected all trophic levels and groups within a marine ecosystem. As they wrote in *Nature* (19 August 2004), “not only is the marine pelagic community responding to climate change, but the level of response differs throughout the community and seasonal cycle, leading to a mismatch between trophic levels and functional groups.”

An orchestra with instruments once playing in harmony is now completely out of tune.

Dave Karl at the University of Hawaii and colleagues are finding the same disturbing results through a different time-series investigation of plankton at Station ALOHA, a stationary site 100 kilometers north of the island of Oahu. Through data obtained since 1988 from continu-

ously recording instruments at Station ALOHA, Hawaii Ocean Time-series (HOT) program scientists like Karl have found that dramatic changes are taking place in plankton communities in the Pacific Ocean. Age-old nutrient cycles are being altered by new kinds of interactions between the ocean and the atmosphere, interactions that stem from global climate change.

“Long-term changes in plankton community structure and productivity in the North Pacific subtropical gyre—the largest ecosystem on our planet—are happening as a result of climate change,” says Karl. Time-series plankton research programs in addition to Station ALOHA/HOT include the Bermuda Atlantic Time-Series Study, the United Kingdom’s Atlantic Meridional Transect, and the California Cooperative Oceanic Fisheries Investigations.

Station ALOHA has given oceanographers a view at the sea’s surface of plankton communities over time. Seeing plankton from space through the lenses of satellites has provided scientists with a different look at how these organisms are responding to climate alterations. From high above the Earth, sensors aboard satellites can distinguish even slight variations in the ocean’s color, variations to which our eyes are not sensitive, says Jim Yoder, dean of the Woods Hole Oceanographic Institution in Massachusetts and a biological oceanographer. Different shades of ocean color reveal the presence of phytoplankton.

As a result of their chlorophyll pigment, phytoplankton absorb the red and blue wavelengths of the light spectrum, which they use for photosynthesis, and reflect green light. “In regions with high concentrations of phytoplankton, the ocean appears green to blue-green on satellite images, depending on the species and density of phytoplankton there,” Yoder says.

Using satellite imagery to look for the reflected green of chlorophyll, scientists have found that phytoplankton in some areas of the seas have declined significantly, while in other regions, plankton have increased exponentially. “Satellite ocean color observations provided the first view of seasonal phytoplankton



A large phytoplankton bloom south of Labrador is visible in this SeaWiFS image. Such satellite images show that plankton cover huge swaths of the ocean surface. Photograph: NASA's SeaWiFS Project and Orbimage.

cycles at regional to global scales," Yoder says. "A new perspective on phytoplankton variability in the global ocean was the result."

Through data from satellite imaging instruments such as the coastal zone color scanner, SeaWiFS (sea-viewing wide field-of-view sensor), MODIS (moderate resolution imaging spectrometer), and others, oceanographers gained an understanding of shifts in seasonal patterns over large areas of the global ocean and discovered important differences between plankton cycles in the Southern Ocean

and in Northern Hemisphere oceans. "Understanding phytoplankton and related ocean variability is crucial if we hope to separate natural cycles from the potential impacts of human activities," says Yoder.

Revenge of the plankton

In the tale of climate change versus ocean plankton, these tiny creatures may have the last word.

In much the same way humans need antioxidants to reduce cellular damage, phytoplankton produce organic sulfur

compounds that act as a defense against the damaging effects of sunlight and ultraviolet (UV) radiation. Through this mechanism, plankton play a major role in regulating the global climate system.

The cycle begins when plankton produce dimethyl sulfide (DMS). Plankton transfer DMS to ocean waters, where it then evaporates to the lower atmosphere. In air, DMS breaks down into sulfur compounds that become the nuclei around which clouds form. When there are more clouds, less sunlight and less UV radiation reach Earth. With lower levels of sunlight and UV radiation, phytoplankton produce less DMS, slowing the cycle.

David Siegel of the University of California–Santa Barbara found that UV radiation is responsible for 90 percent of the production of DMS by plankton in summer, when sunlight is most direct. "Summertime DMS production is enormous," says Siegel. "The implications are huge. We now know that phytoplankton respond dramatically to increasing sunlight and UV radiation."

As global climate change accelerates, more UV radiation will reach the surface layer of the oceans as Earth's protective ozone shield is stripped away. Phytoplankton will produce more DMS in response to increased UV radiation, causing increased cloudiness. "This effect may help to slow or lessen climate change, but it would in no way reverse the overall trend," says Siegel.

The story of plankton and climate change ends, as of now, with plankton in the lead. For the time being, the ingenuity of Earth's tiniest creatures is keeping alive—albeit just barely—an ancient tryst of sunlight, sea, and wind.

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Visit these Web sites for more information:

- www.sahfos.ac.uk (Sir Alister Hardy Foundation for Ocean Science)
- <http://ioc.unesco.org/iocweb/co2panel/HighOceanCO2.htm> (UNESCO symposium on high ocean CO₂)
- www.pewclimate.org (Pew Center on Global Climate Change)
- <http://oceancolor.gsfc.nasa.gov/SeaWiFS> (SeaWiFS)