The Invisible Web

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EXPLORATIONS
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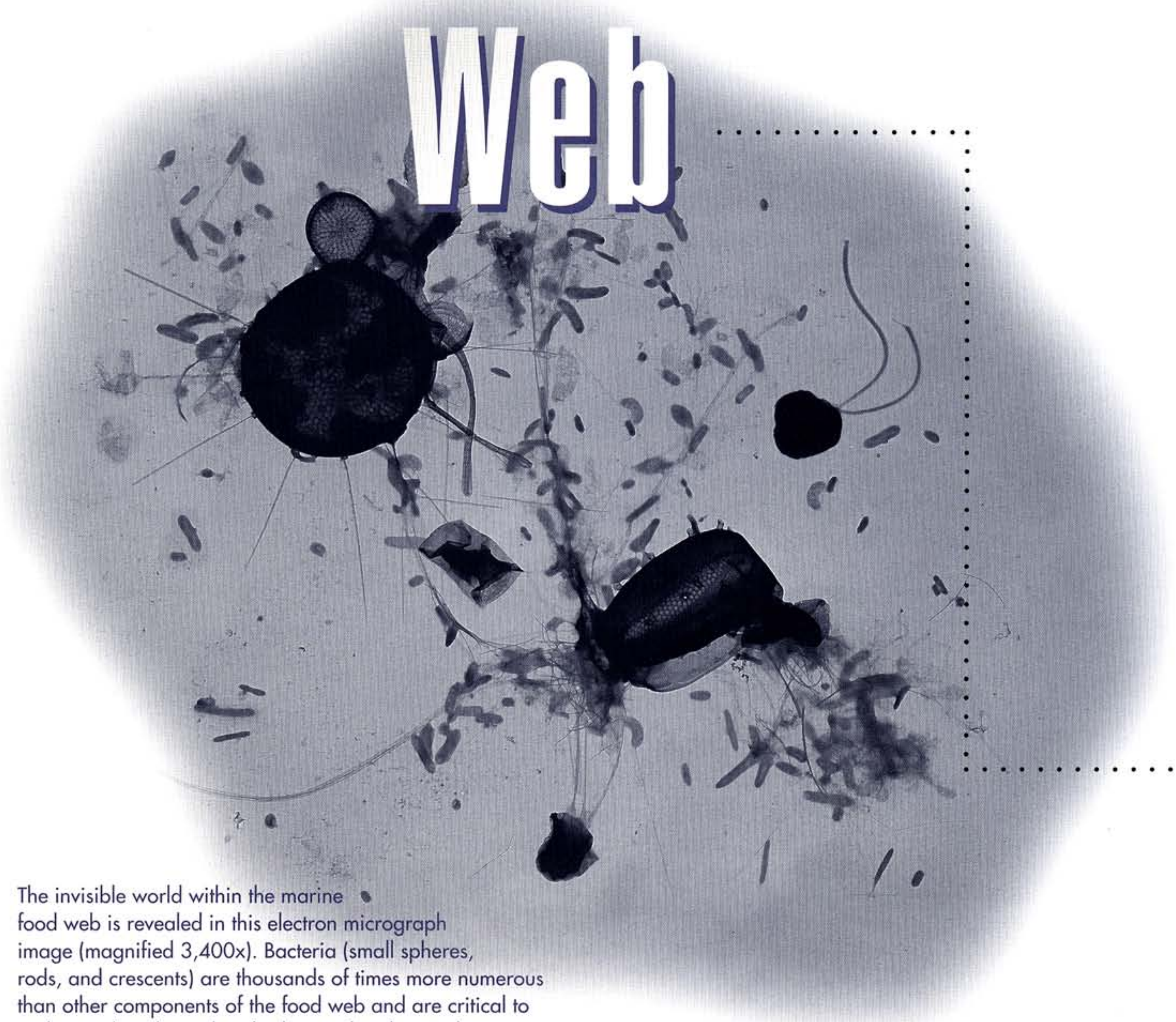
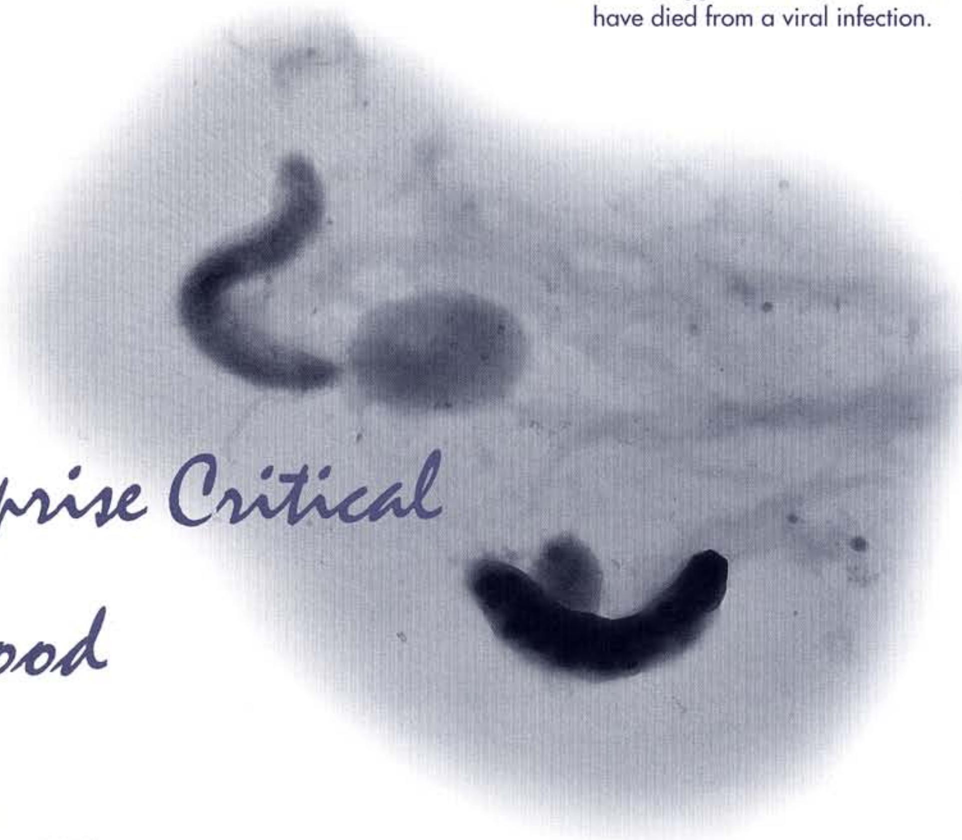


The invisible world within the marine food web is revealed in this electron micrograph image (magnified 3,400x). Bacteria (small spheres, rods, and crescents) are thousands of times more numerous than other components of the food web and are critical to understanding the carbon budget and cycling in the ocean. Also present in this image are phytoplankton and protozoa.

At much greater magnification (29,000x), bacteria are shown with a mucous film of organic material in this arctic seawater sample. The presence of viruses inside the crescent-shaped bacterium suggest that it would soon have died from a viral infection.



Bacteria Comprise Critical Link in Food Chain

When most scientists want to make a point, they may hang graphs of their latest experimental results outside their office or give a scientific lecture. But few go to the lengths of Farooq Azam and turn an office into a scale model of the ocean, complete with Styrofoam™ phytoplankton and protozoans hanging from the ceiling.

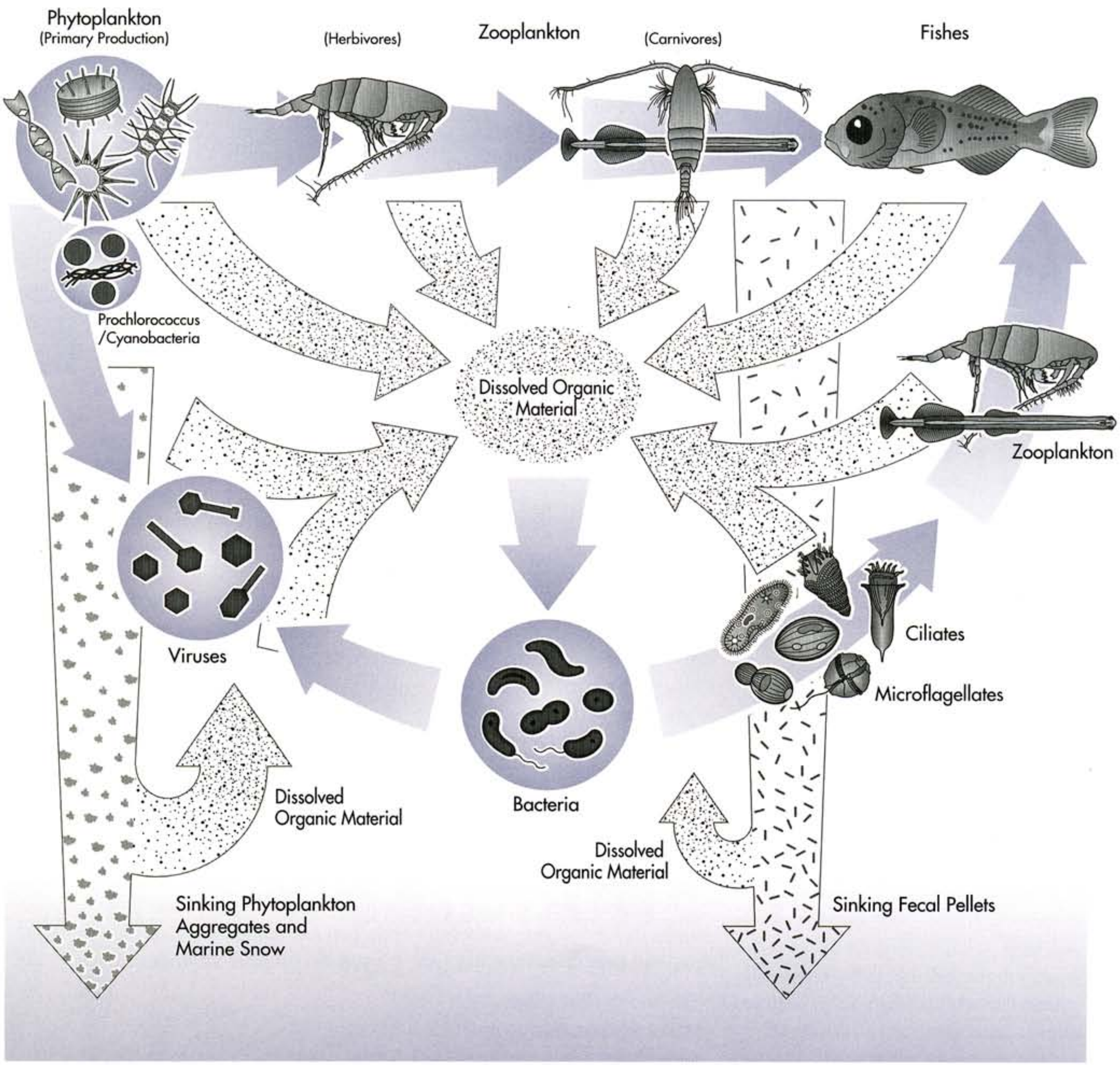
Admittedly, Azam's office represented only a tiny section of the sea—about one cubic millimeter to be exact—and he finally removed the models after a couple of years. But the display depicting a single phytoplankter surrounded by hordes of bacteria and viruses got his message across: the ocean is teeming with microscopic life.

"Until about 15 years ago, people said there were lots of interesting bacteria in the sea, but not enough to make a difference in how the ocean works," said Azam, a professor in the Scripps Marine Biology Research Division. "What we have been blamed for is developing the idea that bacteria in fact play a major role in the ocean's biogeochemistry, carbon fluxes, and nutrient dynamics."

In other words, you can throw out that model of the food chain you were taught in school: the one where little fish eat plants, big fish eat the little fish, and people eat the big fish. It's not that simple anymore.

The Marine Food Web:

This illustration shows the importance of bacteria in the marine food web. Phytoplankton convert carbon dioxide into organic material through photosynthesis. They are the primary food source and suppliers of carbon to the food web. Though it was long believed that the dominant pathway in the food web proceeded from phytoplankton to fishes, (left to right along the top) it is now well established that a major flux of carbon to bacteria also occurs through the pool of dissolved organic material. Bacteria are a critical link in returning some of this material back into the food web through a pathway known as the microbial loop (arrows to the right from bacteria). Bacteria may also be killed by viruses (arrow to the left) with much of their carbon returning to the dissolved organic material. As bacteria consume the dissolved material, they also release nutrients that facilitate the growth of phytoplankton. In another important role, bacteria not only consume dissolved organic material, they also further break it down with enzymes. Sinking aggregates and fecal pellets are the essential source of food for life in the dark depths of the ocean; however, they strip nutrients from the surface waters. By quickly dissolving some of these particles, bacteria help to keep nutrients in the upper layers of the ocean. In turn, these nutrients can be used by phytoplankton to create more food for the web. Without these salvage and recycling activities, the ocean would quickly become a vast desert.



The new model portrays a complex web that includes the significant role played by bacteria. Scientists once thought that the main function bacteria served in the ocean was to decompose dead organisms, but they now realize that these microscopic cells provide vital links among marine life of all sizes.

Unlike most larger creatures, bacteria take up as food organic matter that is dissolved in seawater. When the bacteria are eaten by tiny protozoa and crustaceans, which are in turn feasted on by fish, these vital nutrients are passed throughout the food web.

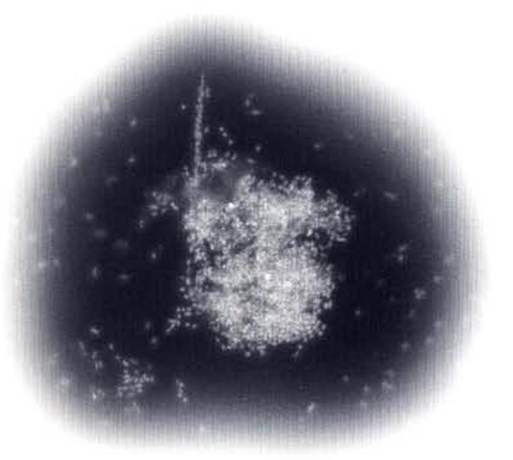
Azam, a native of Pakistan, was first introduced to the study the food chain when he came to Scripps in 1969 as a postdoctoral fellow. He decided to focus his research on marine bacteria, an area that had received almost no attention until that time.

"Frankly, I got into it quite naively," Azam said, reclining in a leather beanbag chair in his office overlooking Scripps Pier. "What intrigued me was the lack of knowledge on the subject. I found it hard to believe that bacteria did not play much of a role."

Azam's interest soon turned to studying the role that marine bacteria play in cycling carbon in the ocean.

Postdoctoral researcher Hans-Peter Grossart prepares a sample for microscopy. Grossart is examining interactions between bacteria and diatoms in microcosm experiments.

While scientists have long thought that the ocean acts as a carbon "sink" by absorbing carbon dioxide from the atmosphere, the fate of carbon in the oceans has remained pretty much a mystery. How important a role bacteria play in processing carbon could determine whether the world's oceans will be able to absorb enough carbon dioxide to prevent the globe



Microscopic image (2,600x) of a "marine snow" aggregate heavily colonized by bacteria. The bacteria will partially dissolve the aggregates as they sink. These aggregates play an important role in the food web as explained in the illustration on the facing page.

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from heating as a result of greenhouse warming.

"Ultimately, the game is to be able to predict how the oceans are going to behave in the future," Azam said.

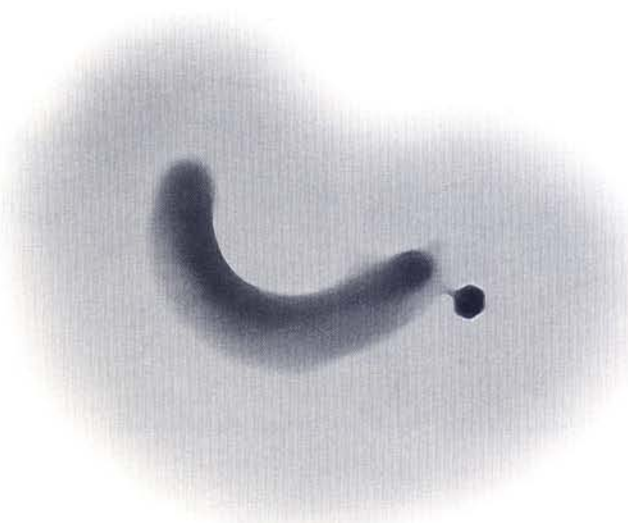
About 6 billion tons of carbon are spewed into the atmosphere each year in the form of carbon dioxide as the result of human activities such as the burning of fossil fuels. Roughly half of this carbon is thought to be taken up during the process of photosynthesis by the huge masses of phytoplankton at the surface of the world's oceans.

The percentage of this carbon that sinks to the ocean floor and is buried, as opposed to being recycled back into the atmosphere, will be determined in large part by bacteria. The carbon taken up by phytoplankton tends to sink to the ocean floor in the form of organic matter. Bacteria interrupt this process by breaking down a large percentage of organic matter before it reaches the seafloor. When these bacteria are subsequently eaten by protozoa, the carbon is emitted as carbon dioxide in shallow waters, from where it can once again be released into the atmosphere.

In fact, Azam's work indicates that about 50 percent of the carbon

Postdoctoral researcher Grieg Steward prepares a sample for examination by electron microscopy, which provides extreme magnification and is important in the study of marine viruses.

The first step in viral infection of a bacterium is the attachment of the virus to the cell, shown at 50,000x magnification (bottom left). The virus injects its nucleic acid into the bacterium, which then directs the cell to synthesize more viruses inside. A marine virus shown at 80,000x magnification (below).



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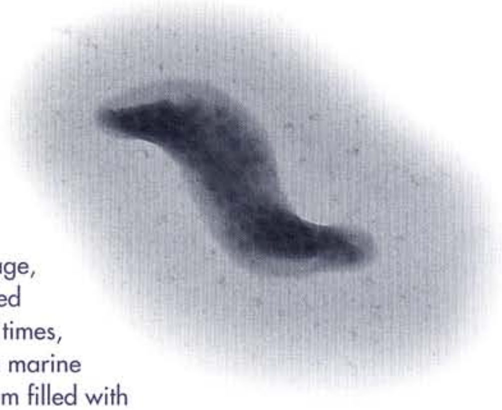


This image, magnified 40,000 times, shows a marine bacterium filled with replicated viruses. The viruses will eventually cause the bacterium to burst.

Postdoctoral researcher David Smith (rear), loads samples of bacterial DNA into a thermal cycler. Graduate student Richard Long examines fragments of bacterial DNA. Such techniques of molecular genetics are providing a deeper understanding of the ecology of bacteria in the sea.

in the ocean may by channeled through this so-called "microbial loop."

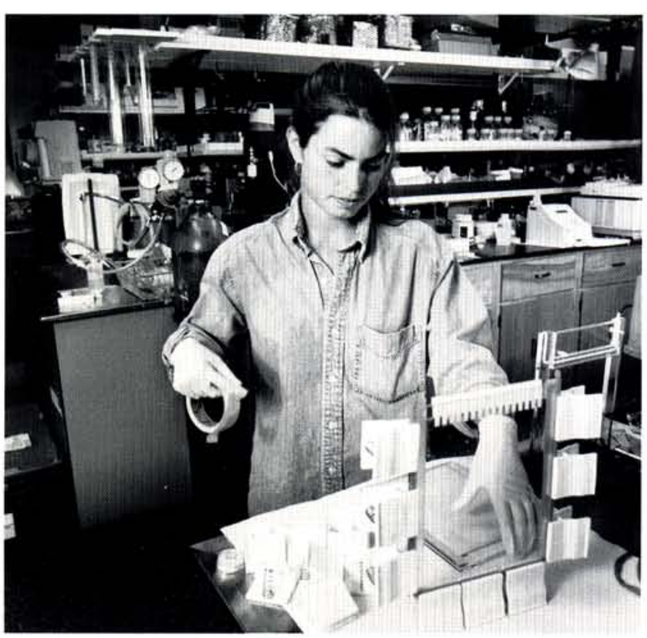
"People knew that some carbon is taken up by bacteria and that, yes, this microbial pathway exists," said Azam. "But the magnitude was not known. We quantified it and it turned out to be a major pathway. Thus, in the event atmospheric carbon dioxide levels increase, the ability of the ocean to sequester carbon would be reduced because of efficient carbon respiration by the organisms constituting the microbial loop."

Azam is quick to point out, however, that the process varies significantly from ocean to ocean. In the Southern Ocean around Antarctica, for example, the temperature at great depths is not that much colder than at the surface. Thus, ocean waters are very well mixed, and carbon deposited near the ocean floor is quickly recycled to the surface.

Azam also is interested in studying how the food web in antarctic waters works given that the region experiences long periods during which the sun never rises above the horizon.

"During the antarctic winter, no phytoplankton are produced because there is no light," he said. "We have proposed that bacteria are storing up food, which then supports the energy requirements of the food web during the dark period."

Azam theorizes that during the antarctic summer, bacteria feast on dissolved organic matter that is easy to degrade while matter that is difficult to assimilate piles up. The bacteria then turn to this stockpile of food during the long winter months.



Graduate student Laura Fandino studies bacterial diversity and population dynamics. Methods using DNA sequence analysis are now revealing a rich diversity of "new" bacteria and their roles in the functioning of marine ecosystems.

Farooq Azam and David Smith collect samples at Palmer Station, a scientific base in the Antarctic.

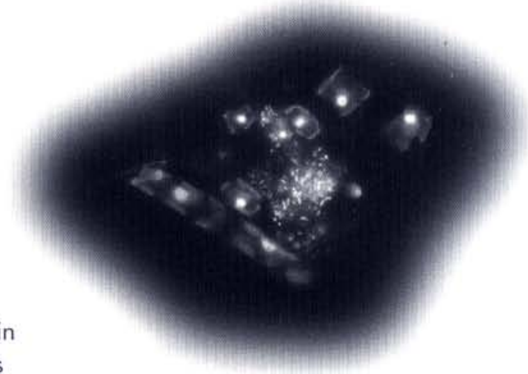
"The bacteria are stretching the food supply out through the dark period," Azam said. "The bacterial biomass produced at the expense of dissolved organic matter provides the energy for other life forms to survive through the winter."

Azam believes a similar phenomenon may be occurring in the Arabian Sea, where powerful monsoons occur. During the summer, winds carry moisture-laden air from the Arabian Sea north over the subcontinent, producing heavy rainfall. This pattern then reverses during the winter, when dry air from the Asian interior is carried across India toward the ocean. These huge swings in weather cause striking changes in the levels of nutrients that are brought to the ocean surface.

"During the monsoon that occurs in July and August, you have a huge input of plant nutrients from the deep water into the surface layer, which is exposed to much more light, causing huge blooms of phytoplankton," he said. "But when the rains quiet down, the nutrient influx is very low because the deep water, which is very rich in nutrients, is no longer being brought to the surface. That causes a period of very low productivity."

Visiting scientist Vera Zutic uses an innovative electrochemical technique to study the adhesion of bacteria to surfaces. Adhesion is a survival strategy for some bacteria, enabling them to colonize particles and to interact with other organisms.

A healthy bacterium is seen here next to one in the last stage of a viral infection (25,000x). Virus has caused the bacterium to burst, allowing the newly produced viruses to spill into the seawater. Bacterial remnants contribute to the dissolved organic material at the center of the food web.



This image shows the abundance and diversity of microbes in seawater. Researchers are challenged to develop ways to study ecological interactions at the space scale relevant to bacteria, and to understand what enables a bacterial species to survive in the sea. We can then understand the role of bacteria in the ocean's ecosystem as a consequence of their strategies for survival.

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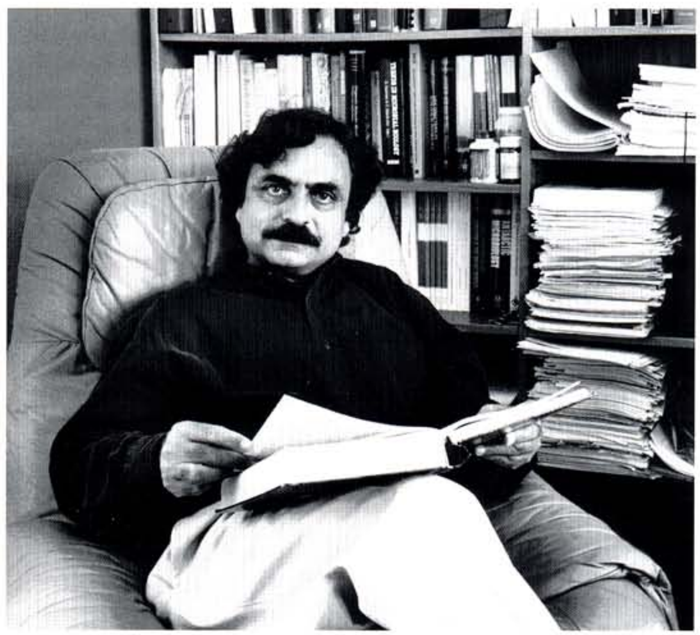

Azam relaxes in his office overlooking the beach.

Azam recently conducted a series of experiments in the Arabian Sea. He theorizes that, as in antarctic waters, the pool of dissolved organic matter, which is used mainly by bacteria, plays an important role in carbon cycling. Dissolved organic matter accumulates during the period of high plant photosynthesis and provides the energy base for continued high bacterial activity into the period of low plant productivity. As a result, bacteria cause more carbon dioxide to be released into the atmosphere than phytoplankton take up.

"In the postmonsoon period, the ocean actually becomes a significant net source of carbon dioxide," Azam hypothesizes.

The finding could have important implications for how the world's oceans may respond to dramatic changes in weather associated with global warming.

"If global warming really comes about, then oceans other than the Indian Ocean may also experience strong physical forcing due to high winds," he said. "So one can see this as a model of how some oceans may behave with respect to processing carbon."

A quiet-spoken man, Azam has received major awards for his contributions to the understanding of marine bacteria, including the Rosenstiel Award in Oceanographic Science in 1984 and the G. Evelyn Hutchinson Medal in 1995. Several of his graduate students also have gone on to pursue high-profile careers in the fields of marine bacteriology and virology.

Yet despite being one of the first scientists to investigate the role bacteria play in the ocean, Azam balks at any attempt to label him as a pioneer of his field.

"Let's just say I was there," he said, with a chuckle.