The Plankton-Climate Connection

Growing evidence suggests that one-celled marine plants play an important role in determining the earth's climate

By RICHARD MONASTERSKY

For more than 3½ billion years, the earth has provided the exact mix of water, gases and temperature that life, as we know it, requires for existence.

Is this a fortuitous occurrence? Has life been riding around on a huge piece of rock that has luckily furnished suitable accommodation? Or has life taken part in the process, creating for itself a cozy environment that can support plankton, pandas and a panoply of other earthly organisms?

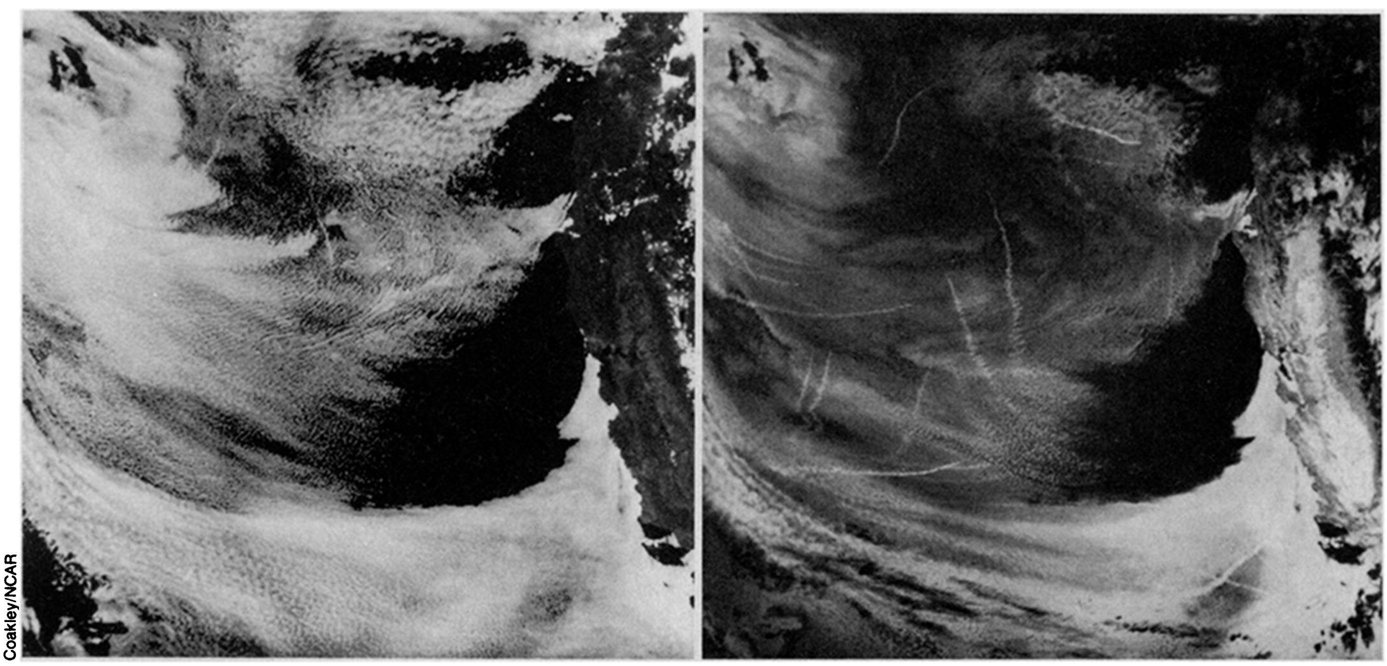
These are the questions raised by a controversial theory called the Gaia hypothesis. Proposed in the early 1970s by British scientist James E. Lovelock, working with biologist Lynn Margulis of Boston University, the Gaia hypothesis states that life has regulated and stabilized the environment, keeping it within the narrow bounds that allow life to continue.

And now, microscopic marine plants are floating into the Gaia debate.

Evidence is emerging that these one-celled plants, called plankton, are at least partially responsible for setting the temperature of the earth. And the new findings are enhancing scientists' understanding of how life can influence the global climate.

The discovery of a previously unknown plankton-climate connection is enough to raise the eyebrows of many scientists. But it's only part of the story.

Almost all scientists accept the idea that life influences the environment, and there are many examples to support this statement. Two billion years ago, for instance, blue-green algae developed the ability to photosynthesize with water — a process that caused atmospheric oxygen concentrations to rise from nothing to the present 21 percent. Another example is the role of plants and animals in determining the atmospheric levels of carbon dioxide and methane — the so-called "greenhouse" gases that are apparently raising the earth's temperature today.



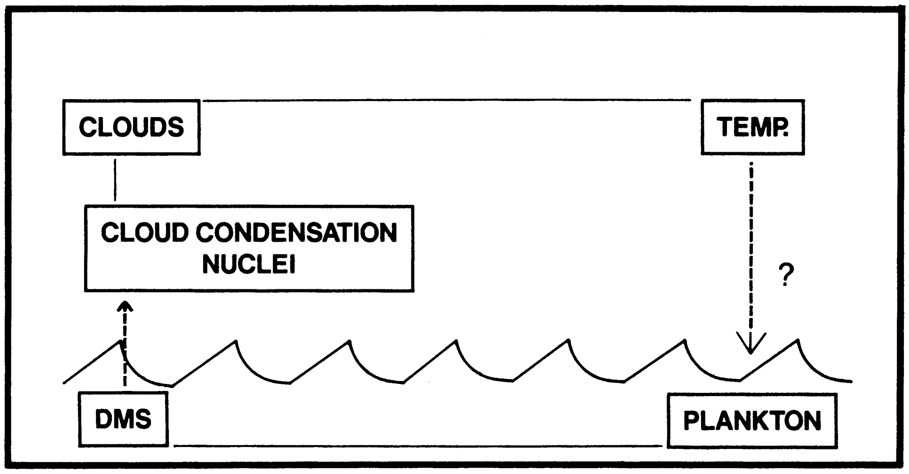
Coakley/NCAR

The link between plankton and climate was strengthened by satellite images, such as these, of tracks caused by ship pollution, which proved that the reflective properties of clouds depend on the number of particles present in the cloud. In the left image, constructed with light from the visible spectrum, only one faint track is apparent in the center (although computers can discern more subtle areas of increased reflectivity that are generated by the ships). These reflective tracks show up clearly in the right image, constructed with longer-wavelength light outside the visible range.

"There isn't any question but that life has had, and has, a tremendous impact on the properties of the terrestrial environment," says James C.G. Walker, an atmospheric scientist at the University of Michigan at Ann Arbor and an avowed critic of Gaia. "The Gaia hypothesis goes a good bit farther than that. It says that organisms not only affect [the environment] but regulate it or buffer it."

According to the Gaia hypothesis, life actually stabilizes certain aspects of the environment, such as the surface temperature of the earth, the composition of the atmosphere and other planetary qualities. Like a thermostat controlling the temperature of a house, the organisms of the earth regulate the environment and prevent conditions from straying into regions that would prohibit life, or so the theory says.

Scientists are just beginning to understand that plankton and climate are linked, and the exact terms of the relationship are still unclear. But what excites many researchers is the possibility that this might be an example of a Gaian relationship. Perhaps, say Gaia supporters, these plants behave like a living thermostat, maintaining the earth's temperature at a comfortable level — a suggestion that is stimulating both experiment and debate.



In the ocean, plankton produces DMS, which accumulates in the seawater. DMS then diffuses into the atmosphere and undergoes reactions that allow these particles to serve as the condensation nuclei for developing cloud particles. The number of cloud particles influences the reflectivity of clouds, which in turn affects the surface temperature of the earth. In this sequence of steps, an increase in plankton productivity will help cool the earth. But it is still unclear how temperature affects the productivity of plankton. If an increase in temperature causes plankton to produce more DMS, then the relationship is helping to stabilize the temperature of the earth. This type of relationship, called negative feedback, would support the Gaia hypothesis.

How is it that such tiny creatures can even affect the climate in the first place?

It turns out that certain species of plankton produce a chemical compound that is important in the formation of clouds. And the number of clouds affects the earth's climate because clouds reflect much of the sun's radiation, sending it back into space. Airplane travelers who have looked out on a blindingly bright field of white are well acquainted with this reflectivity.

The chemical link between plankton and clouds is a sulfur compound called dimethylsulfide (DMS). Inside the plankton cells, DMS protects against the high salt concentrations of the outside seawater. The cells excrete DMS as a normal metabolic product, but the compound also enters seawater when plankton are eaten or die. DMS then diffuses from the seawater into the atmosphere.

For decades, says Gaia author Lovelock, this was the extent of the scientific knowledge about DMS. Nobody really questioned the subsequent fate of the compound. "They thought it was just a biochemical curiosity," he says. But in the 1970s, research into the Gaia hypothesis prompted Lovelock to examine the world's sulfur budget in detail, which meant keeping close track of all the important forms of sulfur. And this continued interest in DMS helped reveal its climatic role.

While Lovelock was musing on the fate of DMS, Robert Charlson of the University of Washington in Seattle was working independently at the other end of the problem. As an atmospheric scientist, Charlson had been wondering how marine clouds grow. Clouds are actually composed of particles of water. But before they can develop, there must be some sort of nuclei onto which water can condense.

Says Lovelock, "It was a speculation by Bob Charlson: Where did the cloud-condensation nuclei come from? We talked about DMS, and it seemed natural that it could be the source."

Earlier this year, in the April 16 NATURE, Lovelock, Charlson and their colleagues proposed that once DMS reaches the atmosphere, it oxidizes to form sulfate particles, which then serve as condensation nuclei for developing cloud particles.

Scientists widely believed — though they had not proved it at the time of the paper — that the number of cloud particles determines the reflective properties of clouds. An increase in the number of condensation nuclei was thought to make marine stratus clouds reflect more sunlight. These types of clouds cover 30 percent of the world at any time, says Charlson, so an increase in their reflectivity would cut off much of the radiation that reaches the ocean surface, thereby lowering the water's surface temperature.

According to the theory, if plankton produced more DMS, the surface of the earth would get cooler.

Within the last several months, new evidence has confirmed the major links in this plankton-climate chain. Charlson, with Timothy S. Bates and Richard H. Gammon of the Pacific Marine Environmental Laboratory in Seattle, reported in the Sept. 24 NATURE that they found a direct correlation between DMS levels and the numbers of cloud nuclei in portions of the Pacific.

These researchers found that the number of nuclei in the area they studied varies with both season and latitude, and that a markedly similar relationship applies to the DMS concentrations in the seawater. This supports the theoretical prediction that DMS is providing the particles that serve as the condensation nuclei for marine stratus clouds.

The next step in the plankton-climate theory linked the number of condensation nuclei to the reflectivity of clouds. Scientists have understood this theoretical relationship for years. If a cloud has a certain amount of water and the number of available nuclei increases, explains Bates, "it means that the given water vapor is spread out more, and you have more surface area to reflect incoming solar radiation."

But that relationship had gone untested until this year, when James A. Coakley and his colleagues noticed that the exhaust from ships left long, highly reflective trails in marine clouds — an effect that showed up on satellite images (SN: 9/12/87, p.168). Because exhaust is chiefly made up of different kinds of particles, the observation showed that an increase in particles over the ocean could raise the reflectivity of clouds, says Coakley, of the National Center of Atmospheric Research (NCAR) in Boulder, Colo. He reported his findings in the Aug. 28 SCIENCE.

In conjunction with previous knowledge about the climate, these new pieces of evidence are helping to convince scientists that plankton *can* influence global temperatures by affecting the planet's general reflectivity. Says Lovelock, "I think the importance [of the new information] is considerable. It highlights a climate mechanism which is as large as or larger than the carbon dioxide-greenhouse [effect]."

There is no doubt that countless other biological and geophysical systems are also involved in determining the earth's temperature. For now, researchers cannot gauge the relative importance of the plankton factor.

However, with the aid of computer models of the climate, it is possible to test how a specific increase in the number of condensation nuclei would likely affect the temperature. According to Charlson, "A 30 percent increased change in the [nuclei] number cools the globe at the surface by 1.3 kelvins, which is a huge climate change." In comparison, during the last Ice Age, when ice sheets covered what is now New York City and much of the rest of the globe, the world was only 4 kelvins colder than it is today.

The recent findings have prompted Lovelock, Charlson and their colleagues to wonder whether the plankton-climate connection is an example of a Gaia-like process. To answer that question, they need to determine whether the relationship involves what scientists call a negative feedback loop — a condition required by the Gaia hypothesis.

Feedback loops are "circular" processes in which two elements of a system affect each other simultaneously. They come in two varieties: negative and positive. Negative feedback reduces any changes in a system and therefore helps to stabilize it. If negative feedback were active in the plankton-climate relationship, then a shift toward warmer temperatures would stimulate plankton to produce more DMS. This would create more clouds, bringing temperatures back down.

Positive feedback, on the other hand, helps destabilize a system. In this process, warmer temperatures would cause plankton to reduce DMS production, which would warm the earth even more. While negative feedback works like a thermostat, positive feedback works like an amplifier.

In the grossest sense, some form of negative feedback must be involved because if the temperature of the earth

Gaia: The life of a theory

The Gaia hypothesis symbolically arose out of the lifeless dust of the red planet. In the late 1960s, NASA was beginning to plan the mission that would later send the Viking spacecraft to Mars, and British scientist James E. Lovelock was helping the agency develop ways to test for the possible presence of martian life.

Lovelock proposed that no probe need actually visit Mars to determine that life does not grace that planet. He reasoned that if Mars supported life, then earthbound scientists could detect signs of organic activity through observations about the martian atmosphere.

In examining our own planet, Lovelock noted that the earth's atmosphere is an unstable, potentially explosive mixture of gases. Life, he proposed, uses the gaseous layer encircling earth both as a source of raw materials and as a repository for waste. This kind of interaction has kept the atmosphere from reaching equilibrium.

In contrast, scientists knew that the atmosphere of Mars — like that of Venus — is made almost entirely of carbon dioxide and is in a state of equilibrium. To Lovelock, this stability indicated that Mars was devoid of life.

In the early 1970s, he expanded on these ideas and coauthored the Gaia hypothesis with biologist Lynn Margulis of Boston University. In essence, the theory states that the lower atmosphere of earth is part of life itself. The plant and animal populations interact with that atmosphere and regulate certain aspects of it, including its temperature and chemical composition.

Some scientists attacked the theory for being teleological or implying that life must be working toward an optimal end. They said the theory required that organisms be altruistic, behaving in a way that helps the aggregate of life. In general, however, the theory received little scientific attention. "Up till now," says Lovelock, "people tended to ignore it."

Rather than attracting the interest of scientists, the Gaia theory originally found support in an ironic mix of extreme ecology groups and industrial polluters, says climatologist Stephen H. Schneider. The ecologists interpreted Gaia as implying a unification of life. And the industrialists translated it as a license to pollute, on the premise that life would counteract any deleterious effects from pollution.

The Gaia theory does not actually support the latter idea. By extension, it does imply that life may help the earth recoil from the effects of human pollution, but the process would take millions of years. And when earth finally recovers, humans might not be around to appreciate the revitalized planet.

In recent years, however, the Gaia hypothesis has started to achieve an air of scientific legitimacy. Lovelock, Margulis and others have reacted to the early objections and have refined the definitions of the theory. Moreover, they have helped illustrate specifically how Gaia might work by proposing regulatory mechanisms such as the plankton-climate relationship. Says Lovelock, "There's a lot of excitement and interest. And I think a lot of what I will call Gaia-fence-sitters are beginning to feel uncomfortable with their position on the fence."

Scientists are by no means suddenly embracing the theory in record numbers. Many do not accept the idea of long-term regulation and argue that the environment has changed throughout earth's history, sometimes causing extinctions on a massive scale. Others, like James C.G. Walker of the University of Michigan at Ann Arbor, believe that if any process is regulating the environment, it must be the inorganic geophysical systems of the earth.

Regarding Gaia, says Walker: "I think that's something that you really just believe or you don't believe, because it's quite hard to prove the case. My personal belief is that's simply not how life works."

But in contrast to earlier times, the general scientific community is now beginning to debate seriously the evidence for and against Gaia. Next March, an international conference sponsored by the American Geophysical Union will convene eminent scientists from disparate fields to explore the hypothesis.

Whether scientists accept or reject the theory is not a major concern of Lovelock's. He says he's primarily delighted that it is stimulating research. "All that matters at this stage of the game," he says, "is that they don't just ignore it, and that they go out and experiment and try to prove it wrong."

As a case in point he mentions that it was the Gaia theory that prompted scientists to discover the relationship between plankton and climate. "What's exciting about all this is that by following our noses along a certain trail, we're finding a lot of interesting science."

— R. Monastersky

dropped far enough, the production of DMS would near zero. In this situation, clearer skies would allow sunlight to proceed unhindered to the earth's surface, where it would help warm the environment.

However, even Charlson is not willing to place any bets on how the system operates within the normal range of temperatures. "We really don't know the nature of this feedback system," he says. "The possibility does exist that this is a thermostat. The possibility also exists that this is, at least at times, a destabilizing feedback."

In his examination of DMS concentrations and atmospheric particle number, Bates did find subtle indications of an active negative feedback. "When you plot DMS [emissions] versus solar radiation, you see that where solar radiation is highest, DMS [emissions] are also highest. That would suggest negative feedback," he says. This means that in the summer months, when temperatures are high, more DMS was produced in the areas he studied. The added DMS was helping to cool the climate.

He cautions, however, that these observations are far from proof that the worldwide population of plankton is actually stabilizing the global temperature. At the heart of the matter, nobody really understands how the climate affects the total plankton population. Laboratory experiments have tested how certain species of plankton respond to different environments, but no models as yet have matched the complexity of the real oceans.

While some species of plankton readily produce DMS, others produce almost none. Therefore, biologists must address the complex question of how climate shifts influence the competition between different plankton species.

Further complicating the feedback question is new evidence that plankton were involved in a positive feedback system during the last Ice Age. At the recent American Chemical Society meeting in New Orleans, French researcher Robert Delmas presented findings that 20,000-year-old Antarctic ice contained higher-than-average numbers of particles derived from DMS.

This means that when temperatures were colder than normal, plankton – at least near the Antarctic – were creating high numbers of cloud particles, which would cause temperatures to drop even further.

"That would suggest that this is an amplifier – that under those conditions anyway, [the plankton-climate relationship] reinforces the existence of an ice age," says Charlson, who has recently returned from visiting Delmas at the Laboratory of Glaciology and Geophysics of the Environment in Grenoble, France.

Scientists from varied disciplines are now attempting to quantify the two-way relationship between plankton and the climate. Through ocean observations, ice core data from Antarctica and laboratory experiments, researchers hope to determine when this system may have served to regulate temperatures, and perhaps when it has destabilized temperatures, spurring the spread of ice over large sections of the earth.

For those involved in the Gaia debate, the plankton-climate relationship represents a chance to study feedback on a refreshingly concrete system. In the past two decades, many scientists have complained that the examples raised in support of Gaia are untestable and far too general.

Says Gaia coauthor Margulis, "This kind of work does not solve or prove the Gaia hypothesis, but it provides mechanisms, which can be tested."

Concerning the proposed plankton-climate relationship, Stephen Schneider, an NCAR climatologist and sometimes Gaia-critic, says, "I like it a lot. It's testable, which is certainly not true of a lot of other parts of Gaia. And it's clear cut: We can measure it. It may not be fundamental; we don't know yet. But it's a nice link and I think it should be pursued." □