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Celebration of Earth Day 2011

Sea and sky. The marine biosphere as an agent of change*

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Resum. La vida oceànica, i particularment el plàncton microscòpic, influeix en el clima a llarg, mig i curt termini: a llarg termini, mitjançant la configuració dels cicles d'elements essencials per al funcionament de la Terra com a sistema; a mig termini, amb l'intercanvi amb l'atmosfera de gasos d'efecte hivernacle, i a curt termini, amb l'emissió de gasos traça i partícules que afecten les propietats químiques i òptiques de l'atmosfera. Aquest article se centrarà en els efectes a curt termini. L'oceà representa una font principal de sofre, iode i hidrocarburs a la troposfera i, essent immens com és, rivalitza amb els continents com a emissor d'aerosols primaris en forma de cristalls de sal, polímers orgànics i microorganismes. Aquest alè del mar, de fort component biogènic, regula la capacitat oxidativa de l'atmosfera i influeix en el balanç d'energia del Planeta per mitjà del protagonisme que té en la formació i l'opacitat dels núvols. Els esforços internacionals d'integració de dades globals, i molt especialment de la informació registrada des de satèl·lits orbitals, han fet evident —tot i que sembli sorprenent— que la vida marina no solament influeix en el comportament dels oceans, sinó que deixa una petja diària també al cel; una prova més de la fascinant arquitectura del complex sistema que és el nostre Planeta viu.

Paraules clau: regulació marina · aerosols · formació de núvols · albedo · plàncton· Gaia

Summary. Ocean life, and particularly microscopic plankton, influences climate in the long, medium, and short term: in the long term by shaping the element cycles that are essential to the functioning of Earth as a system; in the medium term, through the exchange with the atmosphere of greenhouse gases; and in the short term, through the emission of trace gases and particles that affect the chemical and optical properties of the atmosphere. This article will focus on the short-term effects. The ocean represents a major source of sulfur, iodine and hydrocarbons to the troposphere and, being as immense as it is, it rivals the continents as an emitter of primary aerosols in the form of salt crystals, organic polymers and microorganisms. This breath of the sea, of a strong biogenic component, regulates the oxidative capacity of the atmosphere and influences the planet's balance of energy through its role in the formation and opacity of the clouds. The international efforts for the integration of global data, and particularly of the data registered by orbiting satellites, has made it clear that, as surprising as it may seem, marine life not only influences the ocean's behavior but also leaves a daily trace in the sky; another piece of evidence about the fascinating architecture of the complex system that is our living planet.

Keywords: marine regulation · aerosols · cloud formation · albedo · plankton · Gaia

Let us imagine for a moment that we are with the crew of *Apollo 17*, the last expedition to set foot on the Moon, and we have the great privilege those men had of seeing Earth from space. In Fig. 1, we observe what the crew saw, an image that has been sent around the world. We see the textures of the Earth, which is covered with clouds, a fact that has tremendous implications for our climate.

Why is it so important whether or not there are clouds and what textures and colors Earth has? Because the Earth's energy balance, which ultimately determines climate, especially average temperature, depends heavily on colors and textures. We know that, of the radiation coming from the Sun, a part is reflected immediately and another part is absorbed and then dissipated as heat. There are many routes for dissipation, but in the end, almost 100 % of the Sun's energy reaching Earth returns to space again.

The clouds and albedo

Albedo, the reflecting power of a surface or the ratio of reflected radiation from the surface to incident radiation upon it, in

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Fig. 1. *Apollo 17* hand-held Hasselblad picture of the full Earth taken on 7 December 1972, as the spacecraft travelled to the Moon in the last of the *Apollo* missions.

this case, the short-wave energy returned to space, depends on a surface's color and textures. We all know that if we wear a white t-shirt in the summer we will be cooler than if we wear dark colors.

The albedo of the oceans, which occupy most of the earth's surface, is very low because they are very dark. Approximately 10 % of the radiation is reflected and 90 % is absorbed. The albedo of vegetation zones is slightly higher and in desert areas even more so, with snow and ice having the highest albedo, i.e., they absorb much less energy. The average albedo of the Earth's surface, with no atmosphere and no clouds, would be about 0.15, in other words only 15 % of the Sun's radiation would be absorbed and the rest would return to space. But in reality, Earth is covered with white clouds of varying albedos, between 0.3 and 0.8, and in many cases they reflect most of the incoming radiation. Consequently, the Earth's real average albedo, including the atmosphere, is 0.30, double the value of an Earth with no clouds (Fig. 2). This is key to understanding weather patterns and therefore to our interest in understanding why there are clouds, where they are, why there are less or more of them, and what determines their albedo. And since clouds over the ocean have a much greater cooling effect than clouds over ice or snow, which would reflect much of the radiation anyway, the former are particularly important to understand.

But clouds also retain a part of the heat that is dissipated from the surface. Roughly, we could say that clouds have a dual function, acting as a 'parasol' by reflecting energy, and as a 'blanket,' by retaining energy. There are several factors that determine which is the dominating function. For example, during the day clouds serve more as parasols and during the night more as blankets. High clouds, i.e., the cirrus clouds formed by ice crystals, are better blankets than parasols. They are more efficient at retaining the long-wave energy that is dissipated from the surface than at reflecting solar radiation. Low clouds, however, i.e., the stratus clouds that dominate over the oceans, are better parasols than blankets and are thus of great interest

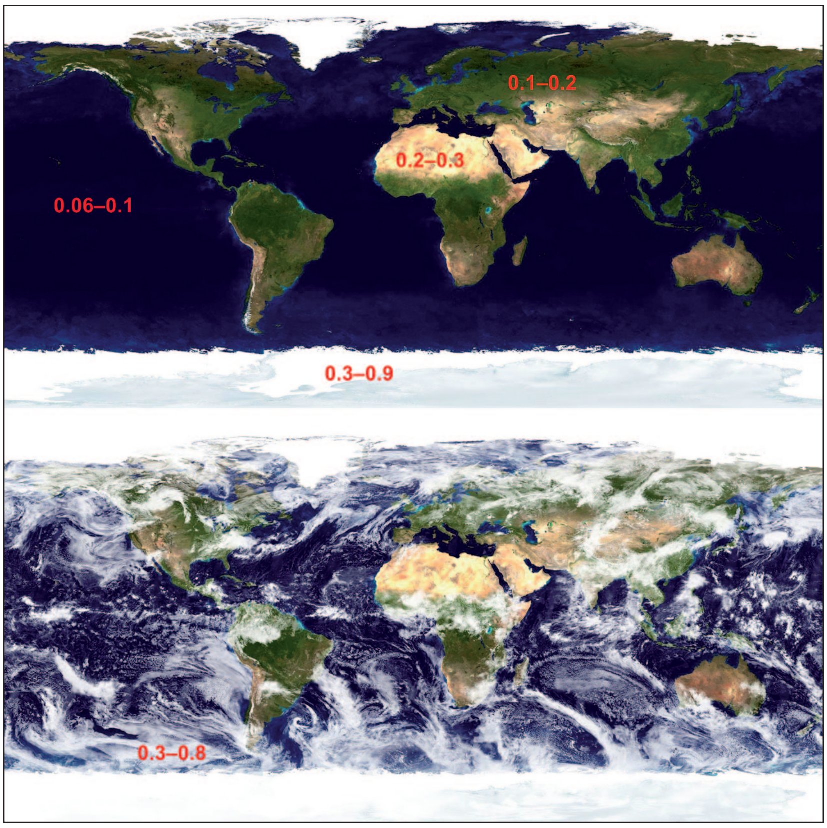

Fig. 2. Images from the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor launched into Earth orbit by NASA in 1999 on board the Terra satellite. Top: Modified image to eliminate clouds and what would be the albedos of oceans, ice, desert and non-desert areas. Average albedo of the Earth's surface = 0.15. Bottom: Earth's albedo with cloud cover. Average albedo of the Earth = 0.30.

when we consider issues related to climate change, as they play an important role in global warming. On average, which of the two functions wins, the parasol or the blanket effect? Over land, clouds have a significant warming effect and over the oceans a cooling one. Overall, clouds are the planet's great coolers. Relative to an Earth completely lacking in cloud cover, clouds represent –20W/m^2 in the planet's energy balance.

How do clouds form?

This question can be traced back to the end on the 19th century. In 1875, Coulier, a French scientist, asked why it was that there were foggier and less foggy days, cloudier and less cloudy days. To determine whether it was only due to water vapor supersaturating the atmosphere, he carried out the following experiment (Fig. 3).

Coulier placed hot water in a flask to super-saturate the air with water vapor. He then created a vacuum, one of the ways in which the condensation of water could be reproduced. According to the knowledge of the time, clouds should have formed inside the flask, but this was not the case. Thus, in a second experiment he filtered the air coming into the flask, but the result was even more negative. He then took the opposite approach, polluting the incoming air. To repeat the experiment today, one could light a match close to the air's entry point, thus generating microparticles. In this third experiment, creating a vacuum resulted in the formation of a cloud inside the flask. In his article, "Note sur un nouvelle propiete de l'air," published in the *Journal de Pharmacie et Chimie*, he concluded that small particles suspended in the air are needed for the formation of fog or clouds [3]. In 1880, Aitken, a Scottish scientist, carried out exactly the same experiment, unaware of Coulier's finding. He concluded that water condenses in the atmosphere on some solid nuclei, formed by dust particles in the air; if there were no dust, there would be no fog, no clouds, no mist, and probably no rain [1]. For example, when our breath becomes visible on a cold morning the dusty conditions in our atmosphere are revealed. Aitken's article, "On Dust, Fogs, and Clouds," published in *Nature*, received enormous attention, while Coulier's went unnoticed. Years later, Aitken became aware of the 1875 article and was the first to recognize that Coulier's conclusions predated his own, but the scientist famous for this discovery remains Aitken. In fact, Aitken is considered the father of cloud condensation nuclei and the very small particles (< 100 nm) in the atmosphere are known as Aitken nuclei. As often happens in science, one researcher went down in history while the one who actually deserved the recognition did not.

Cloud formation is dependent not only on water vapor but also on particles in the atmosphere on which it can condense. Furthermore, the optical properties of the cloud, in other words the albedo, also depend on the number of particles. If a cloud is formed on a few particles, the water vapor will condense to form larger droplets on fewer particles. A cloud in these conditions will have a lower albedo, will be a less effective parasol and will allow more of the sun's rays to reach the Earth's surface. By

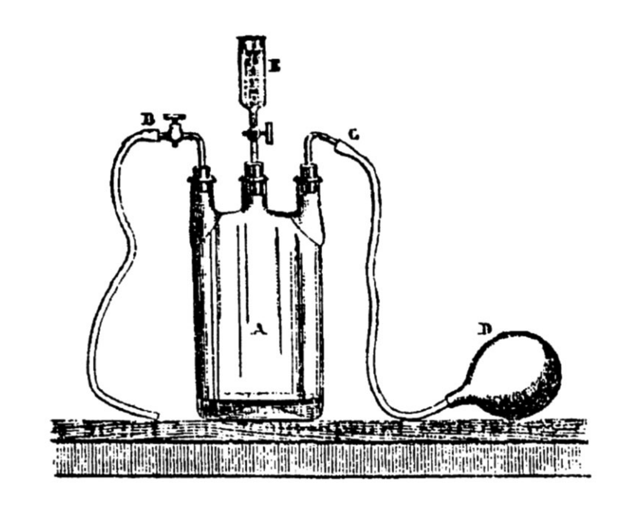

Fig. 3. Original drawing by P. J. Coulier (1875) of the apparatus used in his studies on water vapor condensation. A, water flask; B, entrance of atmospheric air; C, tube connected to D, hand pump to create vacuum; E, liquid water dispenser.

contrast, in the presence of many particles, the same quantity of water vapor will form very small droplets. This cloud will be more opaque to radiation, will have a greater mirror effect, in other words a higher albedo, and is thus a better parasol. Clouds in polluted areas are always much brighter or whiter.

A classic example of one of the many verifications of this effect are ship tracks, which in satellite images are seen as long white strings over the ocean. The ships' exhaust pipes release water vapor, but also a large quantity of sulfates, which give rise to particles favoring the formation of clouds. These clouds, formed on very small particles, are very bright and last for a very long time.

Do particles exist everywhere?

Over the continents there are many obvious sources of particles but in the ocean it is less clear where they come from. In fact, the amount of particles over the ocean can be limiting for cloud formation despite favorable conditions of water saturation. The main sources of aerosols in the atmosphere are primary particles—sea spray, soil dust, smoke from wildfires, and biological particles, including pollen, microbes, and plant debris—that are emitted directly into the atmosphere. Secondary particles are formed in the atmosphere from gaseous precursors; for example, sulfates form from biogenic dimethyl sulfide and volcanic sulfur dioxide (SO_2) and secondary organic aerosol from biogenic volatile organic compounds. Obviously humans are particle emitters of the highest order. When we burn fossil fuels, in addition to CO_2 and water vapor, many particles, from incomplete combustions, are released into the atmosphere as well.

With regard to global change, the formation of clouds and the availability of particles are extremely important considerations. In fact, one of the major uncertainties recognized by the Intergovernmental Panel on Climate Change (IPCC) is the role that aerosols play in global warming or in future trends thereof. Models predict that natural sources of aerosols will not increase during this century, as there are no reasons for them to do so. With regard to anthropogenic sources, a decrease is expected. However, this may depend on the choices made by developed countries, whether the trend will be to burn fossil fuels using cleaner technologies. The combustion of organic matter produces CO_2 but the non-combusted material, with remnants of sulfur, carbon, oil, etc., forms particles in the atmosphere that cause many health problems, especially respiratory illnesses, as well as problems with the decay of heritage sites, among others. For this reason, efforts are being made to reduce the anthropogenic sources of aerosols and therefore, over time, there will be a reduction in the aerosol load in the atmosphere.

Aerosols and global change: a paradox

Today, aerosols play a very important climatic role in the atmosphere, but one that is both very difficult to quantify and very uncertain. On the one hand, there is a direct effect: some aerosols have the intrinsic property of dispersing (cooling) solar radiation and others of absorbing (heating) it. For example, a sulfate aerosol, which is basically condensed sulfuric acid, is quite a 'white' aerosol, with its own microalbedo and the ability to reflect solar radiation; accordingly, sulfate aerosols cool. By contrast, an aerosol from black soot, resulting from unburned fuel, absorbs solar radiation and heats the atmosphere. According to current estimations, there is a fairly important net cooling of –5.4 W/m^2 and a forcing (i.e., how this cooling has changed since the Industrial Revolution) of –0.5 W/m^2.

On the other hand, there are indirect effects, described as the Twomey effect and the Albrecht effect. The first involves the brightness of clouds: clouds formed over more particles are brighter, with a higher albedo, and longer lasting. According to the second, when a cloud forms water condenses in a process that continues until a sufficient mass accumulates such that precipitation occurs, in which case it rains. As previously noted, the greater the number of particles, the smaller the droplets and the longer it will take before it rains. In both cases, more particles mean greater cloud-related cooling. Since the Industrial Revolution, these indirect effects have had an estimated forcing of –0.7 W/m^2.

According to the IPCC (Fig. 4), if we look at radiative forcing, expressed in W/m^2, we observe the effect of different components that have emerged since the Industrial Revolution [4]. We talk about global warming because positive forcing has occurred thus far, but if there had not been a parallel negative forcing, warming would be even greater. What type of cooling has the Industrial Revolution induced? The cooling factors are the changes in albedo due to changes in land use, in vegetation and—with great uncertainty but with a great potential for cooling—the direct and indirect effects of aerosols, alone or in clouds. And herein lies the paradox: if in the future we burn fuels more cleanly, such that fewer aerosols are produced, the Earth will heat up even faster. If we more efficiently burn fossil fuels, we continue to produce CO_2, which has a warming effect, but at the same time we eliminate one of the cooling sources. Consequently, we could say that burning more cleanly is not the solution to global warming, it is not to burn fossil fuels at all and thus to find alternative energy sources.

Marine regulation

We have said that clouds over oceans are very important because the oceans are very dark and account for the majority of the planet's surface. Furthermore, oceans are dominated by low stratus clouds, which exert parasol effects. If we look closer and more specifically at marine sources of aerosols, we can see that there are many of them.

Here I would like to pay homage to James E. Lovelock, who in the 1960s began to observe and to study the differences

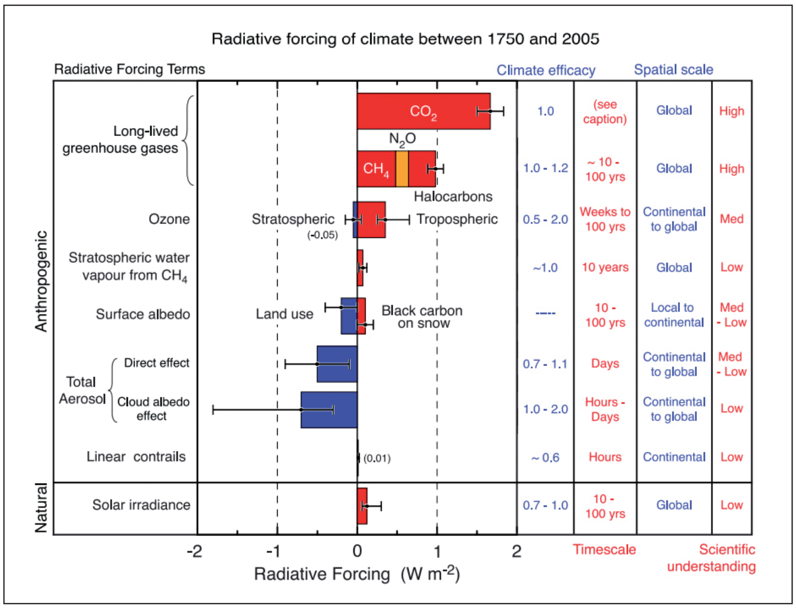

Fig. 4. Principal components of radiative forcing of climate change between 1750 and 2005. Source: IPCC.

between the Earth and other planets. Lovelock arrived at the conclusion that the evolution of the Earth, as a living planet, has proceeded in such a way that the abiotic world and life have evolved together; hence, one cannot be understood independently of the other. This conclusion forms the basis of the Gaia theory: that is, life is not a mere passive agent that adapts to changes (orbital, tectonic, etc.); rather, it is an active agent that in turn modifies its conditions. The Gaia theory has been widely criticized. The staunchest neo-Darwinists, for example, claim that natural selection acts on a gene and that genes know nothing of altruism or climates. Lovelock's response has been that the sum of many genes in a complex system produces 'emergent properties' that lead the system to homeostasis, and that the system is stable precisely because there is life, without the need for each individual gene acting for the well-being of the planet. It can also be argued that we only have the case of planet Earth, that there is no control to confirm that the Earth's solution is the only possible one for a planet with life. Certainly, one of the interesting aspects of Gaia is that it has left us with a deep well of verifiable hypotheses, new ideas, and a holistic view of the planet. Moreover, the response offered by Gaia to the problem of global climate change precedes our enormous concern with this challenge.

One of the many hypotheses embodied in the Gaia theory involves a very specific mechanism. It was observed that on a geological scale the Earth's crust should have been depleted of sulfur many years ago, due to runoff by rivers and rain. Therefore a mechanism must exist by which sulfur is returned from the oceans to the land. Indeed, plankton produces a sulfur gas, dimethyl sulfate (DMS), in small concentrations but steadily and throughout the ocean, resulting in large-scale emissions. Since DMS is a volatile gas, a portion escapes from the oceans to become a major contributor to atmospheric sulfur, while another portion returns to the continents. In addition, Lovelock worked with climatologists specializing in clouds. At the time, analyses of the oceans' aerosols indicated that their main source was basically sulfates; therefore there had to be a source of sulfur that would oxidize to sulfate. With the discovery of the ubiquitous DMS, the problem of cloud-forming aerosols over the oceans was resolved. The implications of this mechanism are very interesting because if plankton produces a substance that ends up forming clouds, clouds filter or reflect solar radiation and plankton partly depends on solar radiation, then these activities form a very interesting, closed Gaian cycle: the greater the amount of plankton, the higher the DMS emissions of plankton, thereby stimulating cloud formation, which reduces the incident solar radiation and thus plankton activity, with lower emissions of DMS, etc. [2] When this cycle was presented, it generated considerable interest, many studies, and thousands of articles, although additional complexities of this cycle have in the meantime been recognized.

Studies on the distribution and dynamics of DMS

At the *Institut de Ciències del Mar – Consejo Superior de Investigaciones Científicas* (Institute of Marine Sciences of the Spanish National Research Council, ICM-CSIC) we have studied this cycle for many years, dividing it into its different components, and carrying out numerous studies on DMS production. It is obvious that plankton does not have a specific gene that tells it to produce DMS so that clouds can be formed; rather, the gas is a metabolic byproduct, just like CO_2, that derives from the interactions between organisms in the planktonic food web. The composition and structure of the plankton community, its physiological status, and its predation activities all contribute to regulate the production of DMS.

Our question was whether the production of this waste product directly responds to changes in solar radiation—and we have determined that it does. Global maps of DMS measurements in all the oceans of the world were compared with the results of climatology studies. The comparisons showed that there is a certain degree of proportionality between the concentration of DMS at a given time at a defined site in the ocean and the amount of radiation received by the plankton at the same time. Thus, plankton may well be responding to solar radiation with the production of DMS [7,8,10].

The next question was the role played by DMS in cloud formation. In the 1980s, when Lovelock and collaborators proposed this cycle, it was thought that aerosols mainly comprised ammonium sulfate; however, analyses of aerosols sampled from the ocean with more sophisticated techniques showed that there are particles of sulfuric acid, soot, pollen, desert dust, organic crystals, and many different mixtures of all these materials. Thus, DMS does not entirely explain cloud formation. In fact, plankton produces not only DMS but also other gases that are precursors of aerosols and, with the right size and chemical composition, will initiate the formation of clouds. In addition, the primary aerosols of marine origin (sea spray) include small sea salt crystals and primary organic aerosols, which are particles lifted into the air when waves break. Bubbles explode and mini-droplets are generated that carry their contents to the surface. Among the secondary aerosols are those that come from biogenic sulfur exhaled by plankton (DMS) and the secondary organic aerosols formed from other volatile organics.

Satellites are very useful tools in global studies of the relationships between the ocean and the atmosphere. From space, satellites can measure the quantity and size of aerosols and of the cloud droplets, and their optical properties. Satellites also give us an idea of the biomass and activity of plankton in the ocean's surface. With data from satellites, we can look for correlations between monthly, and even weekly, data at a global scale. A good correlation between two variables that vary in phase suggests a mechanistic or causal relationship between them. For example, there may be a temporal correlation between the quantity of aerosols of suitable size to create condensation particles and the size of the droplets. The negative correlation we expected happens in most of the ocean [5]. Yet, in order to study the possible effect of the marine biosphere in cloud formation, the origin of these particles must first be determined, i.e., continental, anthropogenic, or marine. Here again, satellites are an essential tool. From the optical properties and the size of an aerosol, and their proximity to fires, urban areas, or deserts, an aerosol can be distinguished and classified according to whether it comprises desert dust, particles of industrial or urban origin, residues from the burning of fossil fuels, from the ocean, etc.

We have studied the temporal correlation between the sizes of droplets and irradiance and determined that the higher the amount of solar radiation throughout the year, the smaller the cloud droplet; which means that clouds with higher albedos are better parasols. Thus, higher amounts of sunlight will yield clouds that are better parasols. The areas where this relationship is not observed are precisely those where aerosols are small and of anthropogenic origin. Naturally, the more sunlight that arrives, the brighter the clouds that reflect the sun will be, except in areas with intense human intervention, which interrupts the natural balance.

At a more regional level, studies have been conducted in a marine area to the east of Patagonia, where there is a recurring bloom of plankton at a particular time during the summer, forming a very predictable patch of chlorophyll. What is the behavior of clouds in this area? Above the chlorophyll patch, the radius of the cloud droplets above it is smaller [6]. This result could be circumstantial, because of the summer rather than the plankton. However, during the same week, the droplets over the area of high chlorophyll were smaller than those outside it. Subsequent calculations showed that this meant an increase in the albedo of the clouds in the area with the greatest plankton production.

The million dollar question

If both on a seasonal scale and on the scale of a phytoplankton bloom, marine biota contribute to an attenuation of solar radiation through the emission of primary and secondary cloud-forming aerosols, could this act as a buffer mechanism for global warming over a scale of decades? Is it possible to estimate whether, by the end of the 21st century, there will be more DMS and more organic compounds from the ocean, and consequently more clouds that in some way are able to buffer climate change? According to current models, ours as well as those of international groups, it seems that emission by marine plankton is responsive to global warming, but the response is not powerful enough to buffer warming [9]. With the results we have as of today, we cannot expect to find a natural solution to global warming.

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