Marine Biogeochemistry & Global Environmental Changes

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Abstract

Taiwan is an island so that it is deeply influenced by the ocean in many aspects, including weather, ecology, environmental changes, and so on. The importance of oceanography research to our life here is obvious. However, both oceanographic research and education started quite late in Taiwan. Few high school science teachers have received sufficient training in oceanography so that it has become difficult for them to successfully deliver oceanography knowledge to their students. That should be one of the major reasons why many educated people in Taiwan know little about oceanography. Although our government is aware of the importance of oceanography education, it takes time and great efforts to establish the content in our high school education system. Taking the advantage of writing this E-news article, I would like to apply popular science style to introduce the fundamental concept of oceanography, particularly focusing on marine biogeochemistry. Further information for oceanography can be found in the pop-science website established by our laboratory: http://www.rcec.sinica.edu.tw/~tyho/lab/popscience.htm.

The Features of Oceanography

Oceanography is not equivalent to marine biology. The core of oceanography is to study the controlling processes and mechanisms for material and energy cycling in the ocean! Let us use the carbon cycle as an example to explain material cycling processes and the unique multi-disciplinary nature of oceanography. Currently, one of the most severe environmental issues on the planet is the problem of global warming mainly caused by increasing carbon dioxide concentrations in the atmosphere due to excessive burning of fossil fuel by human beings. Because of its feature to absorb energy from infrared radiation in the atmosphere, carbon dioxide is one of the most important green house gases controlling the surface temperature of the planet. A major factor in regulating atmospheric carbon dioxide cycling is photosynthesis. Marine phytoplankton (unicellular microalgae) accounts for half of the photosynthetic activity on Earth. The supply of limiting nutrients to the euphotic zone (where sunlight can reach) of the ocean is one of the most important factors in regulating the growth of marine phytoplankton. The processes affecting the supply of limiting nutrients to the surface ocean are closely associated with atmospheric and physical forcing. The effect of physical forces on material cycling starts with the rotation and the revolution of the earth. Earth's rotation and revolution brings diurnal and seasonal cycles of daylight and temperature. These cycles in turn regulate the variations in surface water temperature and sunlight intensity. With the additional influences of the spherical shape of the earth and angle of rotation, surface water temperature and sunlight intensity can vary dramatically within the same day or same season in different oceanic regions. Further, water temperature determines water density. The density differences between oceanic surface water and deep water result in either the sinking of surface water or stratified seawater layers, respectively. The sinking of surface water forms a major driving force for thermalhaline circulation, a global scale water circulation pattern. Moreover, wind-driven circulation, caused by wind (such as monsoons), is the other major driving force for surface water circulation. The movement of oceanic surface water driven by wind, such as Kuroshio current, may also enhance the supply of the limiting nutrients from the subsurface water to the euphotic zone. For example, the nutrients in the subsurface water of Kuroshio current can be transported to the euphotic zone (100-200 m) by physical mixing and the upwelling process when the sub-surface water encounters a shallower region of the ocean floor, such as the offshore water of Yilan and Keelung. The mixing and upwelling processes would cause intensive biogeochemical reactions in the ocean, which greatly enhance phytoplankton growth and deliver the energy and organic carbon to higher levels of organisms in food web. In brief, material cycling in the ocean is closely related to biogeochemical and physical processes. Microalgae transform carbon dioxide into organic carbon and inorganic carbon shells which are further transported to sediment and buried through particle sinking. Given enough time, it is possible that the concentrations of the atmospheric carbon dioxide can be greatly reduced with the net carbon dioxide transport from the atmosphere to the ocean. As shown above, material cycling in the ocean is closely associated with the knowledge and processes of biology, chemistry, physics, and earth sciences. Thus, material cycling in the ocean can influence global environmental change and climate change. Oceanography explores research topics on the global scale. Although whales may seem big, their influence on global material cycling is much smaller than plankton. Even though plankton are small, they grow abundantly and rapidly and they are the favorite of marine biogeochemists!

Marine Biogeochemistry

The cycling of biotic chemical composition is regulated by multiple processes in the ocean, including biological growth and microbial decomposition, physical transport, geochemical reactions, and other processes. These processes take place in the water column of the ocean and its interfaces with the atmosphere and sediment. The investigation of the mechanisms and processes of material cycling is the main subject of marine biogeochemistry. The two main characters in marine biogeochemistry are plankton and its essential nutrients. Phytoplankton rely on essential nutrients to grow and reproduce. At the other end, essential nutrients originate from the microbial decomposition of plankton biomass. Their mutual interaction not only supports the circle of life but also drives the continuous cycling of material in the ocean and on Earth. Compared to other major essential nutrients, carbon dioxide is plentiful in seawater and is rarely a limiting nutrient for phytoplankton growth in the ocean. Instead, nitrogen (mainly nitrate) and phosphorus (mainly phosphate) are not only the major elements found in plankton but are also the main limiting nutrients that regulate phytoplankton growth in the ocean. In addition to carbon, phytoplankton also depend on many other essential nutrients to survive, multiply, and conduct various vital metabolic reactions. For example, protein synthesis requires nitrogen (N) uptake; DNA or RNA replication requires phosphorus (P); and various enzymes depend on a variety of trace metal elements, such as iron. When the supply of all of these essential components is sufficient, the reproduction rates of phytoplankton can double or triple on a daily basis. In other words, when there is a limited supply of essential nutrients, phytoplankton growth and reproduction is then restricted. The major factors that limit phytoplankton growth and reproduction are called limiting factors. In terms of limiting nutrients, as far as oceanographers have known, the three biggest limiting essential nutrients in the ocean are nitrogen, phosphorus, and iron. If you pour these three elements in bioavailable form into the ocean, microalgae will multiply to fill even the mountains and the valleys. At the same time, atmospheric carbon dioxide would be fixed and transported to the deep ocean or the sediment through photosynthesis and particle sinking.

Most of the nutrient supply in the open ocean comes from the subsurface water so that most of the organic matter (about 90 %) generated through photosynthesis is internally recycled (regenerated production) in the surface water of the ocean. Only a small amount of the material is transported to the deep ocean (export production). In contrast to regenerated production regulated by internally recycled limiting nutrients, new production represents the primary production generated by the input of external limiting nutrients. The inputs of limiting nutrients, mainly bioavailable N, P, and Fe, determine new production in the ocean. If the amount of organic matter generated in the surface layer of the ocean is maintained at a steady state, the export production is equal to the amount of new production.

The nutrient concentrations and supply rates in the surface layer of the open ocean are generally low. Thus, phytoplankton biomass is quite low in the surface water of the open ocean. In contrast, nutrient supply rates are relatively high in the marginal seas. Nutrients can enter the ocean through many routes. One of the major pathways is aeolian deposition, such as the input of ashes from volcanic eruptions, lithogenic particles and anthropogenic aerosols brought by storms (Fig. 1). Naturally occurring nutrients in terrestrial systems and those produced by human activity can also enter the ocean via the input of river water and groundwater. The relatively high supply rates of limiting nutrients in the marginal seas thus elevate primary production in the waters.

Phytoplankton are either prokaryotic or eukaryotic. Some prokaryotic phytoplankton, such as blue green algae or cyanobacteria, appeared about three billion years ago. At that time, the atmosphere did not contain oxygen and the chemical composition in the seawater was very different from what it is now. Photosynthesis of blue green algae progressively transformed the ocean and the atmosphere into an aerobic environment. Only after this transformation were various eukaryotic phytoplankton, terrestrial plants, animals, or even people able to come into being. The requirements and capacities to obtain different essential nutrients differs among various phytoplankton groups. For example, the prokaryotic phytoplankton *Prochlorococcus* is able to grow under extremely low light conditions and requires a large amount of intracellular Fe. In order to understand material cycling in the ocean, it is essential to know the distribution of various phytoplankton groups and its environmental controlling factors. For example, relatively large sinking particles generated in surface waters sink faster than relatively smaller particles, so they have higher probability to reach deeper ocean water or sediment to be buried. Diatoms are relatively big and heavy. After death or being grazed by zooplankton and formed into fecal pellets, they have a higher likelihood of generating larger sinking particles (Fig. 2). It can be the opposite circumstance for smaller particles. Unless aggregated, relatively small particles tend to stay suspended in the surface water and are internally cycled.

Trace Metal Biogeochemistry

Understanding the environmental factors constraining phytoplankton activities and community structure is essential to our knowledge of the biogeochemical controls of global material cycling and climate change. In addition to the major nutrients (N and P), trace metals can also limit phytoplankton growth. For example, in the Southern Ocean and equatorial Pacific Ocean, nitrate and phosphate concentrations are extremely high but the phytoplankton biomass is not as high as expected, where is referred as high nutrient low chlorophyll area (HNLC). Oceanographers have demonstrated that the growth of the phytoplankton in the HNLC regions is mainly limited by Fe supply.

My personal research direction is marine trace metal biogeochemistry, focusing on studying trace metal-phytoplankton interaction. Trace metal availability and composition is a major factor regulating phytoplankton growth and community structure in the ocean. However, oceanographers have limited understanding on trace metal availability and composition in seawater. After joining Academia Sinica, I have conducted a series of field studies in the South China Sea and the Western Philippine Sea to study trace metal cycling by using the composition in phytoplankton, suspended particles, and sinking particles to investigate the sources, cycling, and transport of trace metals in the oceanic regions. At the same time, I have established phytoplankton culture facility in our laboratory. We have cultured and maintained about 20 major model marine phytoplankton species, including 6 major eukaryotic and prokaryotic phyla. During the past 5 years, we have focused on studying trace metal requirement of two important phytoplankton groups: *Trichodesmium* and *Symbiodinium*, particularly focusing on their interaction with superoxide dismutases (SOD).

Although the major limiting factor of phytoplankton growth in the ocean is nitrogen, diazotrophic (nitrogen fixing) cyanobacteria transform dinitrogen (N_2) to ammonium so that nitrogen fixation becomes a critical process to provide new bioavailable nitrogen to phytoplankton in the ocean. Understanding how nitrogen fixation is regulated in the oceans may shed light on mechanisms controlling carbon dioxide cycling and climate change globally. *Trichodesmium*, a filamentous cyanobacterium, is a particularly important oceanic diazotroph due to its substantial contribution of fixed nitrogen and new production to the tropical and subtropical ocean. Recent, we have demonstrated that Ni elevates cellular superoxide dismutase (SOD) activities and nitrogen fixation rates, indicating that Ni-SOD is involved in the protection of nitrogenase from superoxide inhibition during photosynthesis. Moreover, I have been involved with GEOTRACES study since 2012, an international programme which aims to improve the understanding of biogeochemical cycles and large-scale distribution of trace elements and their isotopes (TEI) in the marine environment (Fig. 2). The detailed information may be found in its website: http://www.geotraces.org/.

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http://www.rcec.sinica.edu.tw/~tyho/lab/popscience.htm.

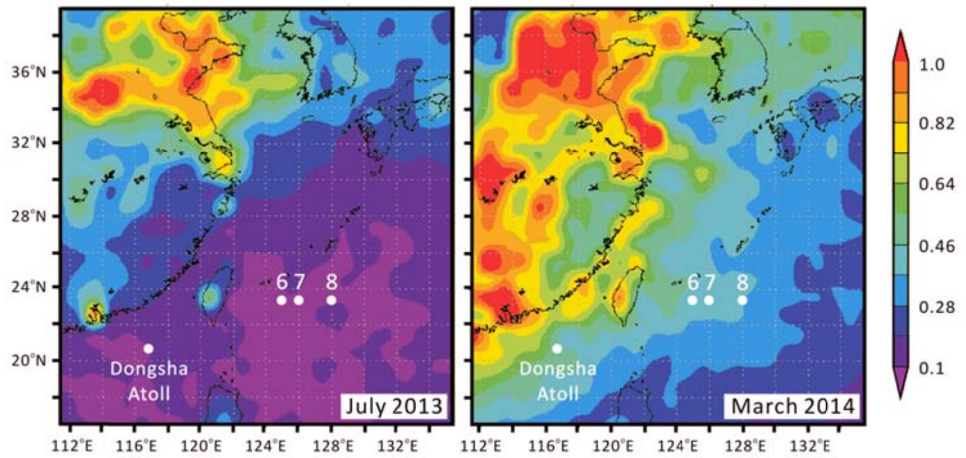

Fig. 1. The comparison of seasonal averaged aerosol optical depths around Taiwan in July 2013 and March 2014 (Wang and Ho, in prep., MODIS images retrieved from http://modis.gsfc.nasa.gov/). The warmer color bars stand for relatively high aerosol concentrations in the atmosphere. The concentrations during winter and spring are much higher than summer and early autumn due to the elevated lithogenic and anthropogenic aerosols transported by the northeastern winter-spring monsoon from East Asia. We have taken samples in the Western Philippine Sea (6, 7, and 8 stations) during the two seasons by collecting aerosols, seawater, suspended and sinking particles to investigate how the aerosol deposition regulates trace metal biogeochemistry in the oceanic region.

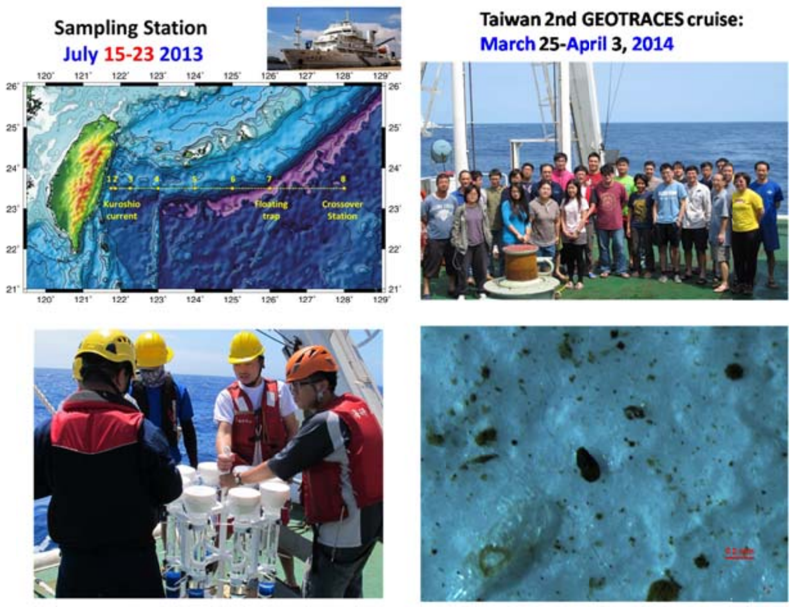

Fig. 2. Taiwan GEOTRACES cruise highlights. Oceanography field studies take great effort to proceed! It requires large research vessel to reach sampling sites where are far from land; it requires the support of unique sampling gears and technical specialists. Moreover, the sampling processes are easily impacted by bad weather. Left-up photo: sampling stations; Right-up photo: the technical staff and research scientists; Left-down photo: trace metal clean floating trap apparatus for collecting sinking particles in the upper water; Right-down photo: the sinking particles collected by the floating trap, which were composed of biotic detritus, fecal pellets of zooplankton, marine snow *et al.* Transported by photosynthesis of phytoplankton and food web, carbon dioxide is transformed to organic particles then is delivered to the deep water or sediment. This process is called Biological Pump. The mechanisms regulating the process and velocity of Biological Pump is a major research topic of marine biogeochemistry.