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Trends in Ocean Acidification Research

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1 Introduction

The Fourth Assessment Report[1] of the Intergovernmental Panel on Climate Change (IPCC) states that "Warming of the climate system is unequivocal…Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Carbon dioxide is the most important greenhouse gas; and its global atmospheric concentration has "increased markedly as a result of human activities since 1750, far exceed pre-industrial values determined from ice cores spanning many thousands of years." More specifically, the IPCC Fourth Assessment Report says, "The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores."

The increase in greenhouse gas emissions is likely to contribute to further increases in ocean and atmospheric average temperatures and rising sea levels. There are concerns that such increases in greenhouse gas emissions are likely to have a significant impact on the ocean environment, namely, ocean acidification. Currently, ocean water is alkaline, with a pH between about 7.4 and 8.2. As the atmospheric concentration of carbon dioxide increases, the ocean absorbs more carbon dioxide from the atmosphere, making ocean water pH closer to the acidic side of the scale. The IPCC Fourth Assessment Report1] notes that "The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic, with an average decrease in pH of 0.1 units" and that "While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms…and their dependent species." Additionally, in recent years, other research communities have separately stated and warned that the progress of ocean acidification may affect ecosystems.

This report will discuss in detail the significance of ocean acidification research and national and international trends in ocean acidification research.

2 Significance of Ocean Acidification Research

2-1 Mechanism of Ocean Acidification

Carbon dioxide gas absorbed in ocean water (dissolved carbon dioxide) reacts with water to form carbonic acid (H_2CO_3) and its dissociation products, bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}), which exist in solution and whose equilibrium is governed by the following equations.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \quad (1)$$
$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (2)$$
$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \quad (3)$$

Carbonate ion, bicarbonate ion, and dissolved carbon dioxide shall be collectively referred to as the total carbonic acid. The sum of bicarbonate ion and twice the carbonate ion shall be referred to as the carbonate alkalinity. Additionally, dissolved carbon dioxide, carbonic acid, bicarbonate ion, and carbonate ion shall be collectively referred to as carbonates.

When more carbon dioxide diffuses into the ocean, the reactions in (1) and (2) occur from left to right, increasing the concentration of hydrogen ions. Using these hydrogen ions, the reaction in (3) occurs from right to left, decreasing carbonate ion. As a result, bicarbonate ions increase and carbonate ions decrease. For example, one theoretical calculation[2] suggests that if the atmospheric concentration of carbon dioxide is 280ppm, then carbon acid will be 8 μmol/kg, bicarbonate ion will be 1617 μmol/kg, and carbonate ion will be 267 μmol/kg. In contrast, the calculation indicates that if the atmospheric concentration of carbon dioxide is 560ppm, the concentrations will be 15 μmol/kg, 1850 μmol/kg, and 176μmol/kg, respectively. pH is an indicator of the concentration of hydrogen ions; pH decreases as the concentration of hydrogen ions increase. The above-mentioned calculation shows that if carbon dioxide in the atmosphere is 280ppm, pH is 8.15, and that when carbon dioxide in the atmosphere is 560ppm, pH is 7.91. pH=7 is defined as neutral, and in fact, today's slightly alkaline oceans are becoming more neutral. However, this actually means that the oceans are becoming more acidic, and therefore such changes in condition are usually called ocean acidification.

Figure 1 compares the concentration of atmospheric carbon dioxide, surface ocean pH, and surface ocean pCO_2 (partial pressure of carbon dioxide) near Hawaii.[3] It shows that surface ocean pCO_2 increases and surface ocean pH gradually decreases as atmospheric carbon dioxide increases.

2-2 Effects of Ocean Acidification on Ecosystems

There are organisms that have calcareous shells or skeletons in the ocean. Coral skeletons, for example, are composed of crystal forms of calcium carbonate known as aragonite, and bivalve and coccolithophore (phytoplankton) shells are composed of crystal forms of calcium carbonate known as calcite. The ocean surface usually has high concentrations of carbonate and calcium ions, and solid calcium carbonate can stably exist in such an environment (calcium carbonate is oversaturated). If the degree of saturation becomes one or smaller, it may be difficult for these organisms to maintain calcium carbonate shells and skeletons, making it harder for them to live in such an environment. Figure 2 shows a kind of coccolithophore collected from the East Bering Sea shelf in September 2006, when a substantial increase in the number of coccolithophores was observed. Disk-shaped outer shells (coccoliths) are made up of calcium carbonate. The left picture shows a healthy coccolithophore. The coccolithophore in the right picture has deformed outer shells. One cannot necessarily conclude that this particular coccolithophore actually dissolved due to ocean acidification. However, according to some experts, a local pH may decrease when coccolithophores proliferate and actively produce coccoliths. It is thought that coccolithophores can be easily deformed as seen in the right picture if the saturation state of calcium carbonate decreases.

If the environment becomes difficult for organisms with calcareous shells or skeletons to live in, ecosystems may be affected, particularly in the following areas.

-Phytoplanktons are the first level of the food chain and primary producers. In addition, some zooplanktons and shellfish also have calcareous

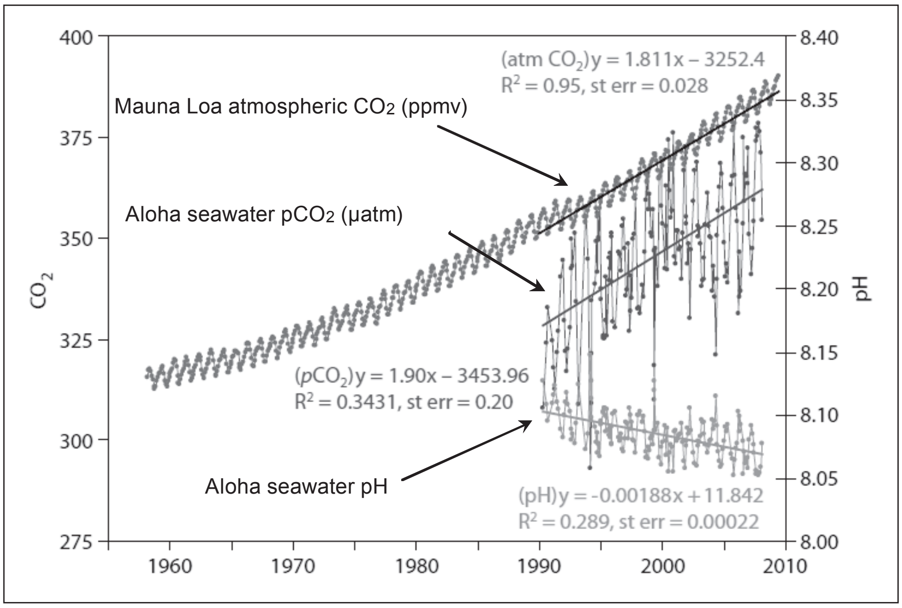

Figure 1 : Atmospheric CO_2 at Mauna Loa and surface ocean pH and pCO_2 (partial pressure of carbon dioxide) near Hawaii (Station Aloha).

Source : Reference[3]

shells and skeletons. Changes in lower levels of the food chain lead to changes in higher levels of the food chain, which may affect the fisheries industry and cause other food problems.

-Biodiversity may be affected. For example, if a coral reef is affected, not only corals but also organisms living in the coral reef are also affected.

However, these are all qualitative tendencies or possibilities. Research[4] has shown that the growth of coccolithophores is hindered when they are cultured under partial pressure of carbon dioxide in a lab. However, there is as yet insufficient evidence to prove this. Even if the degree of saturation becomes one or smaller, shellfish or phytoplankton shells would not necessarily begin to dissolve right away. On the other hand, organisms may be affected by the fact that the saturation state decreases even if the saturation state remains one or larger. It is no exaggeration to say that we barely understand which organisms in the actual ocean may be affected and to what degree, and in particular, we have not yet reached quantitative discussions at all.

2-3 Effects of the Marine Carbon Cycle on Ocean Acidification

It is thought that ocean acidification is caused by the increase in anthropogenic carbon dioxide emissions into the atmosphere. Atmospheric carbon dioxide is taken into the ocean through different processes.[5]

Firstly, carbon dioxide dissolves into the ocean through gas exchange at the ocean surface. The keys for this exchange are the difference in the concentrations of carbon dioxide between the atmosphere and the ocean as well as the solubility of carbon dioxide into seawater. The solubility becomes higher as the water temperature becomes lower. In addition, when seawater becomes heavy due to the formation of high-salinity-water through the process of cooling or freezing, the water moves down from the ocean surface to the middle and the lower ocean. Currents transport carbon dioxide (dissolved at the ocean surface) to the middle and the lower ocean. The dissolution of carbon dioxide from the atmosphere and the transport of carbon dioxide to the middle and the lower ocean through circulations are broadly referred to as the solubility pump.

Biological activities are another important factor. There are two kinds of processes, where organic carbon forms soft tissues and inorganic carbon forms hard tissues. Phytoplanktons fix carbon (produce organic carbon) via photosynthesis. Dead phytoplanktons and other particulate materials are transported to the middle and the lower ocean, and this is called the biological pump. During this process, phytoplanktons at the ocean surface remove carbon dioxide from the ocean and transport it to the middle and the lower ocean. Organic matter is oxidized by bacteria (while it is being transported to the middle and the lower ocean or lying at the top of ocean-floor deposits) and becomes inorganic carbon, increasing the carbonic acid level in the ocean (the increase in the carbonic acid level decreases the ocean's capacity to dissolve carbon dioxide).

Calcareous shells and skeletons (inorganic carbon)

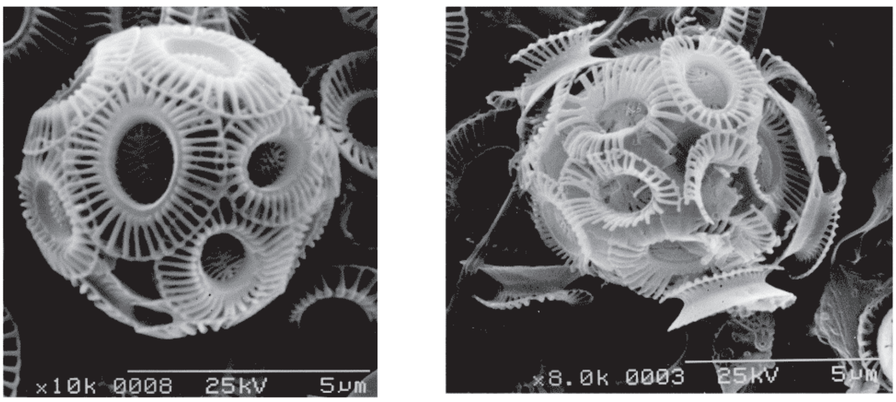

Figure 2 : A kind of coccolithophore collected from the East Bering Sea shelf in September 2006, when a substantial increase in the number of coccolithophores was observed. A healthy coccolithophore (left). A coccolithophore considered to be dissolved (right).

Source : Japan Agency for Marine-Earth Science and Technology produced through biological activities also sink to the ocean floor in particles after organisms die or discharge excrement. When calcium ions (Ca^{2+}) form calcareous ($CaCO_3$) shells and skeletons, hydrogen carbonate ions are also used, emitting carbon dioxide (Equation (4)).

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2 \quad (4)$$

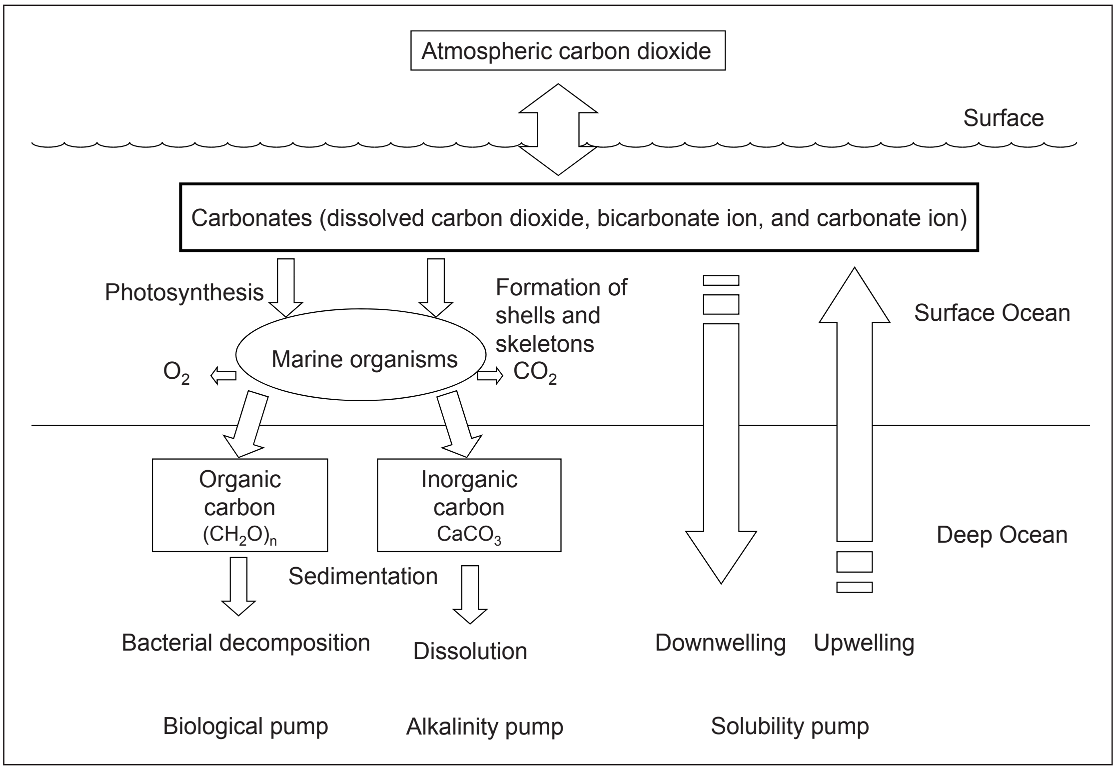

Figure 3 : Mechanism of carbon dioxide uptake into the ocean's interior

Prepared by the STFC

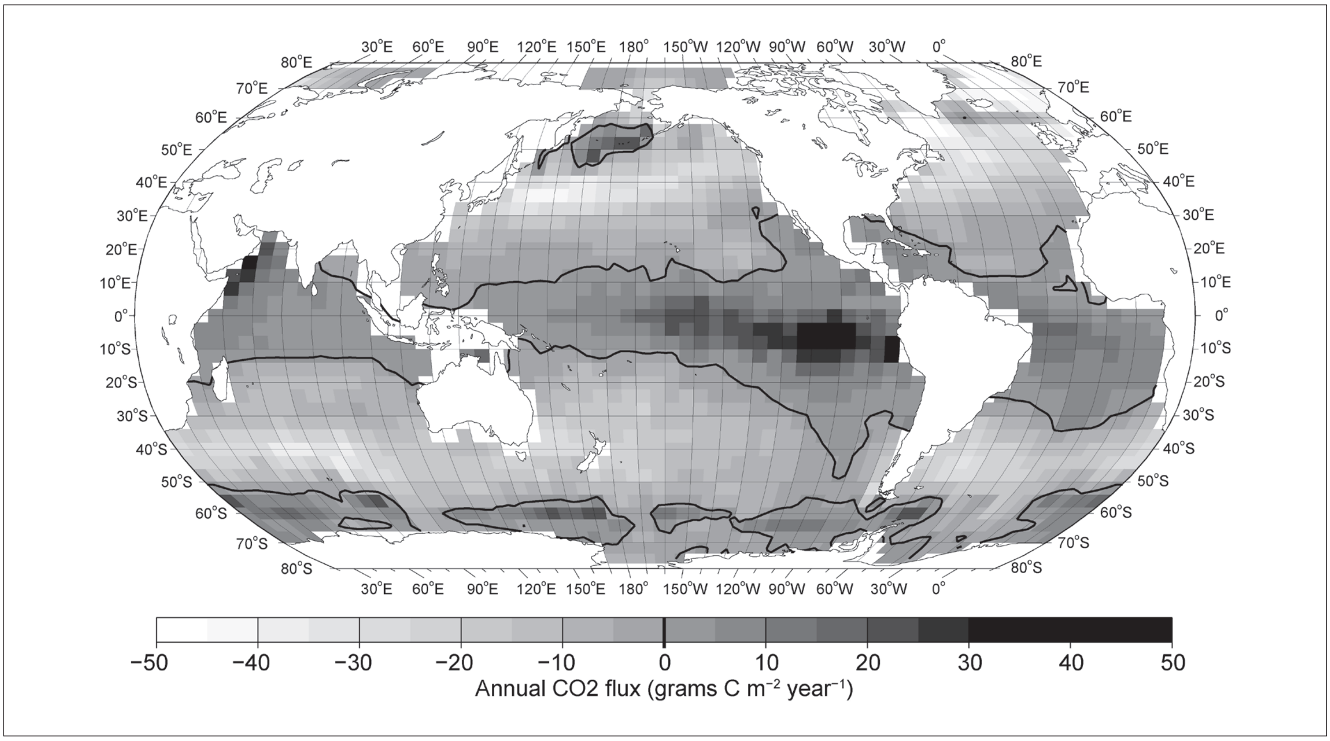

Figure 4 : Mean carbon dioxide uptake per year based on observational data from the past 30 years or so (carbon dioxide flux, converted to the amount of carbon). Positive numbers indicate carbon dioxide emitting areas; negative numbers indicate carbon dioxide absorbing areas. The heavy line indicates zero.

Prepared by the STFC based on Reference[6]

The middle and the lower ocean is unsaturated, and thus, calcium carbonate dissolves when it is transported there, increasing the alkalinity. When the alkalinity becomes higher, the ocean's capacity to dissolve carbon dioxide increases. This process involves changes in alkalinity and is called the alkalinity pump (Figure 3).

The uptake of carbon dioxide is not consistent, as it depends on multiple processes including physical, chemical, and biological processes in the ocean. Figure 4 shows the annual sea–air transfer of carbon dioxide (carbon dioxide flux) based on about three million surface water pCO_2 measurements obtained since 1970.[6] This is so called a climatological mean and does not show the difference in the degree of absorption by year. To understand ocean acidification, it is essential to examine in detail the gap from the climatological mean.

To sufficiently conduct ocean acidification research, it is required not only to monitor the increase in the atmospheric carbon dioxide but also to conduct global ocean observations and research that combines marine physics, chemistry, and biology. The International Ocean Carbon Coordination Project (IOCCP) (jointly supported by the Scientific Committee on Oceanic Research [SCOR] under the International Council for Science [ICSU] and the Intergovernmental Oceanography Commission [IOC] under the United Nations Educational, Scientific and Cultural Organization [UNESCO]) provides web-based communication and coordination services concerning global carbon dioxide-related ocean observations. The Climate Variability and Predictability (CLIVAR) and Carbon Hydrographic Data Office (CCHDO) and the Carbon Dioxide Information Analysis Center (CDIAC) provide actual data.

3 International Context of Ocean Acidification Research

3-1 International Proposals

Ocean acidification is relatively a new area of research. Therefore, as previously discussed, there have not yet been any concrete or quantitative discussions concerning the impact of ocean acidification. Qualitatively speaking, however, it is thought that ocean acidification affects marine ecosystems to a certain extent, and different communities of scientists have separately been making proposals internationally.

(1) Monaco Declaration[7]

In October 2008, the Second International Symposium on the Ocean in a High-CO_2 World was held in Monaco, sponsored by UNESCO and the National Science Foundation (NSF), and the participating scientists announced the Monaco Declaration, expressing concerns about ocean acidification and calling for policymakers to promote research to understand the current conditions and effects of ocean acidification.

(2) Inter Academy Panel[8]

In June 2009, the Inter Academy Panel (IAP) stated that "ocean acidification is a direct and real consequence of increasing atmospheric CO_2 concentrations, is already having an effect at current concentrations, and is likely to cause grave harm to important marine ecosystems." The IAP also stated that reducing carbon dioxide emissions is the only practicable solution, and that the threats of ocean acidification should be recognized at the 15th Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change in December 2009.

(3) Secretariat of the Convention on Biological Diversity[9]

In December 2009, the Secretariat of the Convention on Biological Diversity announced a statement saying, "Ocean acidification is irreversible on timescales of at least tens of thousands of years, and substantial damage to ocean ecosystems can only be avoided by urgent and rapid reductions in global emissions of CO_2."

3-2 Promotion of Research in the United States and Europe

(1) National Academy of Sciences[10]

In the United States, the National Academy of Sciences is conducting a comprehensive research project called "Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment" in response to requests from the National Ocean and Atmosphere Administration (NOAA) and NSF. This project will explore the anticipated consequences of ocean acidification on fisheries, protected species, coral reefs, and other natural resources. The committee for this project is made up of twelve specialists who have degrees in marine physics, marine chemistry, biology, political science, engineering, etc. (as of February 2009). The committee will review current knowledge concerning the impact of ocean acidification on ocean ecosystems, identify critical and key research topics, and recommend a strategy of research for policymakers and the scientific community.

(2) European Project on Ocean Acidification (EPOCA)[11]

In Europe, 27 research institutes from nine countries (Belgium, France, Germany, Iceland, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom) are participating in a four-year research project called "European Project on Ocean Acidification" launched in June 2008 in order to advance the understanding of biological, ecological, biogeochemical, and societal implications of ocean acidification. The research interests of EPOCA are divided into four themes. Firstly, EPOCA aims to document the changes in ocean chemistry and geographical distribution of marine organisms across space and time. Secondly, EPOCA aims to quantify the impact of ocean acidification on marine organisms and ecosystems. Thirdly, EPOCA aims to improve the modeling to better explain how ocean acidification will affect ocean geochemistry and ecosystems. Finally, EPOCA will assess uncertainties, risks, and thresholds related to ocean acidification and present the integrated assessment to policymakers and the general public. To promote research, the members of the project work together in consortium, organizing the Executive Board and the Science Steering Committee. The direction of research and management will be determined during the Consortium's regular meetings based on the advice of the Science Steering Committee. The Executive Board will realize the determination. The Project Office is responsible for overall coordination and is located at the Laboratory of Oceanography of the Pierre and Marie Curie University (Paris VI University) (a joint research unit of the National Center for Scientific Research [CNRS] and Paris VI University). In addition, EPOCA also devote efforts to educating the public by releasing its database.

4 Ocean Acidification Research in Japan

4-1 Experimental Research

(1) Experimental Research of the Effects of Ocean Acidification on Calcifying Organisms[12,13]

This is a three-year (Fiscal Years 2008 to 2010) research project within the framework of the Global Environment Research Fund by the Ministry of Environment. Sea urchins, shellfish, corals, and other coastal benthic organisms with calcareous shells and skeletons are cultured in seawater that has high concentrations of carbon dioxide. The research aims to develop an instrument to control small changes in the concentration of carbon dioxide and, by using the instrument, to create the same conditions expected to occur in the real ocean environment and assess the impact on organisms. The research attempts to go beyond the mere understanding of current conditions and aims to understand the impact of acidification on early life stages of important fishery resources and to consider possible adaptive methods to secure fishery production using farming technology. The research is conducted by the National Institute for Environmental Studies, Kyoto University, the Fisheries Research Agency, the National Institute of Advanced Industrial Science and Technology, and the University of the Ryukyus. Internationally, the research is conducted in cooperation with IOCCP.

(2) Study on Progress of Ocean Acidification and its Effect on Structure and Function of Microbial Community[14]

This research is also a three-year (Fiscal Years 2008 to 2010) research project within the framework of the Global Environment Research Fund by the Ministry of Environment. The study aims to develop a new analytical instrument to accurately measure seawater pH, to understand the conditions of ocean acidification by collecting and integrating existing data, and to find out, mainly through culture experiments, the impact of ocean acidification on marine microorganisms. Based on the results, the study also aims to support international policies to reduce carbon dioxide emissions. The study has already shown that the seawater pH near Japan has decreased (discussed later). The study is conducted by the University of Tsukuba, the Meteorological Research Institute, and

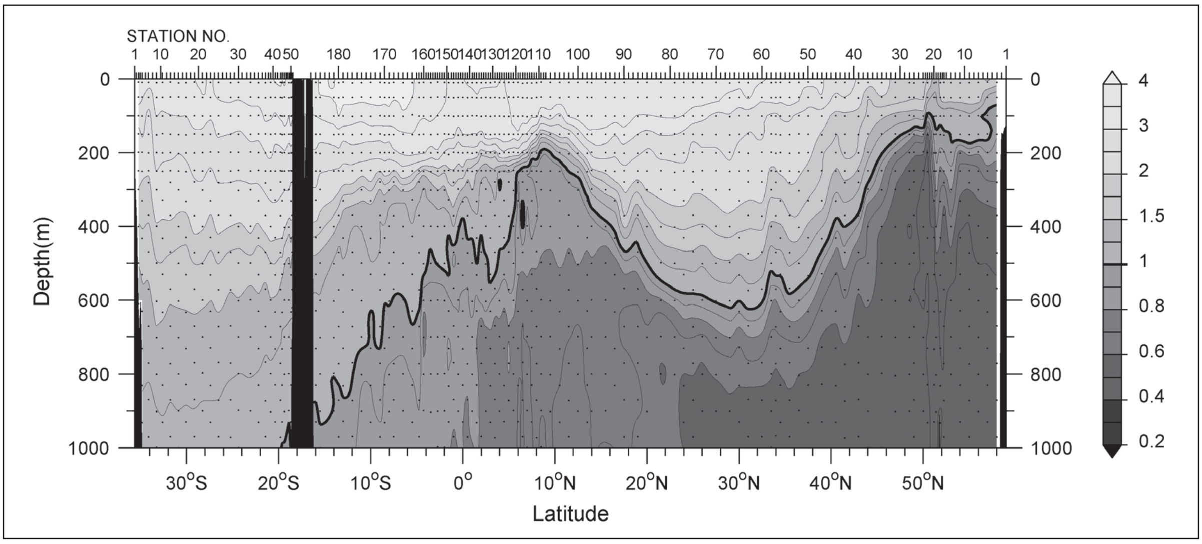

Figure 5 : Saturation state of calcium carbonate along 179 °E (the thick line shows where the saturation state is one)

Source: Japan Agency for Marine-Earth Science and Technology

the Japan Hydrographic Association. Internationally, the study is associated with the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), cosponsored by the International Geosphere-Biosphere Programme (IGBP, sponsored by ICSU) and SCOR.

4-2 Results of Ocean Observation Research

(1) Saturation State of Calcium Carbonate in the Open Ocean

As discussed in Chapter 2, the saturation state of calcium carbonate is an indicator to measure the impact on marine ecosystems. When the saturation state is one or smaller, it is considered to be an unfavorable environment for organisms with calcareous shells and skeletons. The saturation state of calcium carbonate depends on the local water temperatures, pressures, and the concentrations of carbonate ions and calcium ions. In cases where the concentrations of carbonate ions and calcium ions remain constant, the saturation state decreases as the temperature goes down, even if the pressure becomes higher. The concentration of calcium ions can be estimated by the local salinity. Thus, the saturation state can be calculated by measuring the parameters of carbonates (total carbonic acid, partial pressure of carbon dioxide, etc.) in addition to routinely measured parameters such as pressures, temperatures, and salinity.

Figure 5 shows the saturation state of calcium carbonate (aragonite) along 179 °E observed by the Oceanographic Research Vessel “Mirai” in 2007. The vertical axis shows depths and the horizontal axis shows latitudes. The thick line shows where the saturation state is one. The figure shows that it is oversaturated with respect to aragonite above the thick line (where the saturation state is one). Most organisms with calcareous shells and skeletons live in the shallow part of the ocean that is exposed to sunlight (euphotic zone, to about 200m deep in the outer ocean), and therefore, the present open ocean is not necessarily in a dangerous condition from the progress of acidification.

However, observations were made along a similar longitudinal line by a U.S. oceanographic research vessel between 1992 and 1993. The comparison of the parameters of carbonates obtained through the observation and the calculated saturation state of calcium carbonate to the results of the above-mentioned research shows that the saturation state has decreased where the concentration of anthropogenic carbon dioxide has increased.

(2) Seawater pH near Japan[15]

The Japan Meteorological Agency regularly carries out oceanographic and marine meteorological observations using its research vessels every year. The University of Tsukuba and the Meteorological Research Institute analyzed the results of these regular observations within the framework of the Global Environment Research Fund by the Ministry of Environment. The analysis has revealed that the pH of the ocean surface off the Kii Peninsula (at around 137 °E and 30 °N) has decreased by approximately 0.04 in the past 26 years (Figure 6). The decrease in seawater

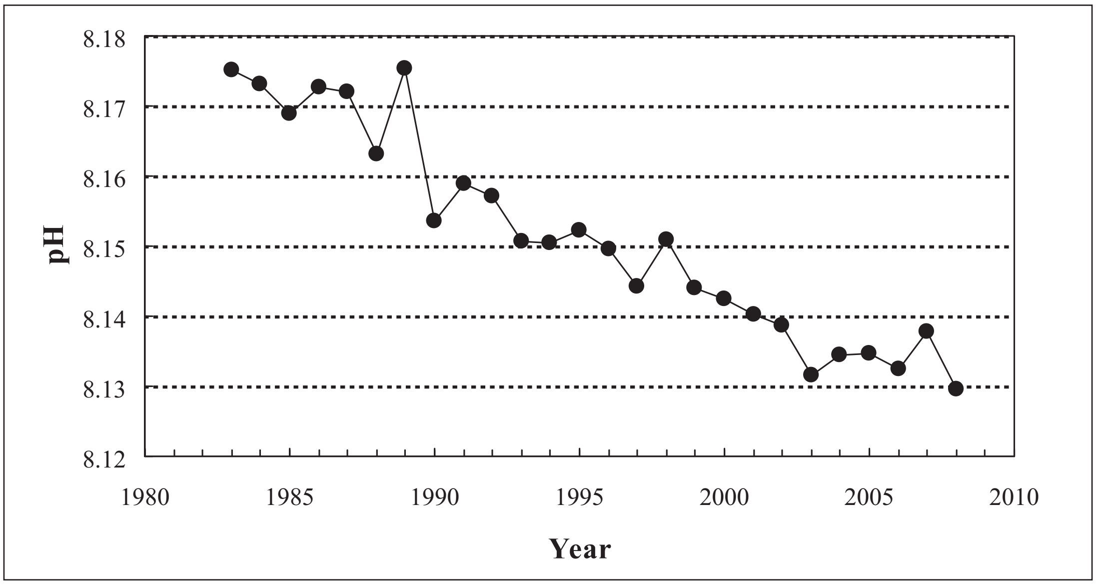

Figure 6 : Decrease in seawater pH off the Kii Peninsula

Prepared by the STFC based on References[15]

pH during the 200 years after the industrial revolution is considered to be about 0.1, and therefore, the study has concluded that seawater pH has been decreasing more rapidly.

(3) Saturation State of Calcium Carbonate in the Arctic Ocean

A joint research team from the Institute of Ocean Sciences, Department of Fisheries & Oceans Canada, and Japan Agency for Marine-Earth Science and Technology suggested that the saturation state of calcium carbonate in the Arctic Ocean had decreased in 2008 compared to 1997, and that the undersaturated area (where the degree of saturation is one or smaller) has been spreading at the center of the Canada Basin of the Arctic Ocean[16] (Figure 7).

The recent rapid melting of sea ice in the Arctic Ocean is an issue. The ice that covers the surface ocean is melting, and more seawater is exposed to the atmosphere, making sea-air gas transfer more active and advancing acidification.

In addition, sea ice meltwater is close to fresh water, and therefore, the concentrations of carbonate ions and calcium ions are low and the alkalinity is also low. Sea ice meltwater dilutes seawater, decreasing the saturation state. The alkalinity is also low in the undersaturated area in the Canada Basin of the Arctic Ocean. This suggests that sea ice melt is considerably affecting the decrease in the saturation state in this area of the ocean.

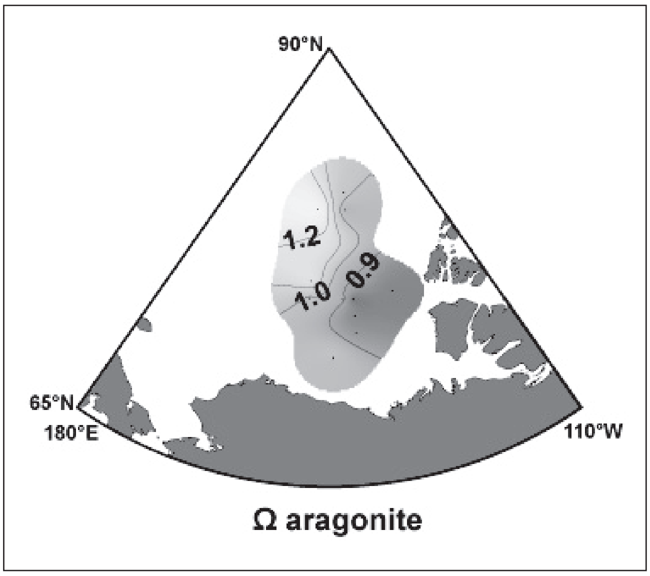

Figure 7 : Distribution map of the saturation state of calcium carbonate observed by Canadian ice breaking vessels. The dots are observation points. The map shows that the center of the Canada Basin in the Arctic Ocean is undersaturated with respect to calcium carbonate.

Source: Japan Agency for Marine-Earth Science and Technology (Reference[16])

4-3 Numerical Simulation Research Results

The Ministry of Education, Culture, Sports, Science and Technology is conducting a five-year program (fiscal 2007–2011) called the Innovative Program of Climate Change Projection for the 21st century in order to contribute to the IPCC Fifth Assessment Report (to be released between 2013 and 2014) and provide basic scientific data for the establishment of climate change

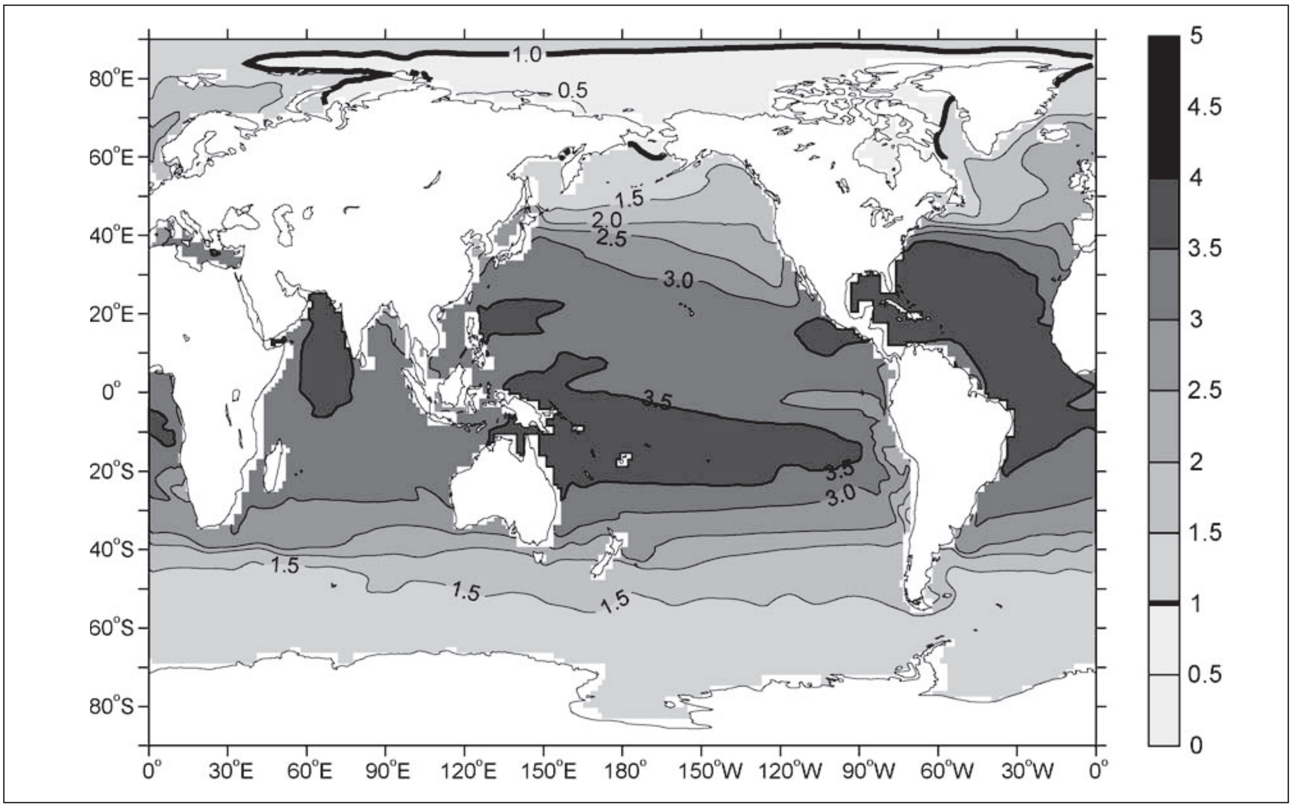

Figure 8 : Saturation state of aragonite at the end of the 21st century. The Arctic Ocean is undersaturated. (The thick line shows the saturation state at one.)

Source: Japan Agency for Marine-Earth Science and Technology (Reference[17]: Calculations by the Innovative Program of Climate Change Projection for the 21st Century was revised.)

policies.[17] This program uses the Earth Simulator to project future climate changes based on different scenarios of carbon dioxide emissions provided by the IPCC. The program also projects changes in the saturation state of calcium carbonate.

Figure 8 is a distribution map of the saturation state of aragonite at the end of the 21st century. The map is based on a calculation in cases where the concentration of atmospheric carbon dioxide is fixed at 450ppm. The progress of acidification primarily depends on the increase in the concentration of atmospheric carbon dioxide, and it is calculated that high-latitude oceans (including the Arctic Ocean, the Antarctic Ocean, and the northern part of the North Pacific Ocean) will become undersaturated with respect to calcium carbonate more quickly. It is thought that acidification in the Arctic Ocean advances due to the melting of sea ice caused by global warming. This result is consistent with the observation results on the Arctic Ocean discussed earlier.

5 Conclusion

Ocean acidification is a relatively new area of study. Qualitatively speaking, acidification affects organisms with calcareous shells and skeletons, and the decrease in seawater pH affects other marine organisms. These changes may create food problems and affect human life. However, since it is a new area of study, current knowledge about the current state of acidification as well as knowledge about the impact of acidification on ecosystems are not sufficient. It is thought that ocean acidification is caused by the increase in anthropogenic carbon dioxide into the atmosphere. Atmospheric carbon dioxide is absorbed into the ocean through various physical, chemical, and biological processes, and therefore, it is necessary to conduct comprehensive research from a wide perspective to understand ocean acidification.

In Japan, as discussed in Chapter 4-1, the research conducted within the framework of the Global Environment Research Fund by the Ministry of Environment is relatively large-scale, combining an experimental study of the impact of acidification on organisms, an observational study to understand the current state of acidification in the actual ocean, as well as the development of required instruments. Taking into consideration the impact of ocean acidification on organisms as well as on humankind, it will be essential to conduct research from a sociological point of view in addition to basic ecological research. According to a survey quoted in the IPCC Fourth Assessment Report,18] Japan's research efforts in understanding the impact of ocean acidification (the area covered by IPCC Working Group II) are inadequate. It will be necessary for Japan to create a framework for interdisciplinary and inter-organizational research, which covers studies on social impacts.

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Profile

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Dr. Kawano specializes in oceanography. He has been studying changes in the ocean environment through observations. In particular, he has been exploring the increase in water temperatures at the bottom of the ocean and changes in the Antarctic overturn system. He also serves as a visiting professor at the Graduate School of Frontier Sciences of the University of Tokyo.

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