Paleoclimate reconstruction and future forecast based on coral skeletal climatology

— Understanding the oceanic history through precise chemical and isotope analyses of coral annual bands —

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Global warming (due to increased carbon dioxide in the atmosphere) has attracted much attention. Yet, predicting trends in the Earth's climate remains difficult. A more sophisticated and accurate global warming model can be obtained by reconstructing climatic change since the Industrial Revolution, and other past periods of warming. To this end, a promising area of research in marine science is coral skeletal climatology, which offers a unique method for accurately reconstructing marine temperature and saline concentration over the past several hundred years, with a high temporal resolution (ca. 2 weeks) based on chemical and isotope analysis of long-lived coral skeletons. This method has been successfully applied to the Little Ice Age around the 18th century and the mid-Pliocene warming period of 3.5 million years ago. It can also be applied to biological and environment studies on massive coral bleaching events caused by unusually high oceanic temperature levels and other environmental issues such as ocean acidification.

***Keywords*:** coral, climate, global warming, ocean, oxygen isotope ratio

1 Introduction

Observation records of the ocean and land at high resolution over a long time span are necessary in order to understand the climate change at a global scale. However, there are very few records of marine observation using measuring equipment before 1950. Therefore, the reconstruction of marine temperature, rainfall, and salinity over the past several hundred years using the annual growth bands from the skeletons of massive reef-building coral colonies has drawn attention (Figs. 1 and 2). The annual bands in the coral skeletons were discovered in 1933, but they became the subject of active research after 1995, and only recently the research has developed into “coral skeletal climatology” (Fig. 3). In this paper, I shall explain why the coral skeleton is excellent as a recording medium of the past global climate change, and describe the major developments where the latest analysis technology is being utilized to read the past records.

Under the title “Paleoclimate” in Chapter 7 of *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*[1] published in 2007, researches on climate changes from several years to several hundred thousand years were reviewed. In this report, there were many citations of the results of marine environment reconstruction at high temporal resolution (about two weeks) using indirect indices such as the oxygen isotope ratio of coral samples from the tropical and subtropical zones. It was shown that the sea temperatures of the recent two hundred years were clearly higher than the past period, through the records left in the extant large corals from several areas of low-latitude waters, and this is considered to be a major accomplishment of coral skeletal climatology. Figure 2 shows the research subjects used in the paleoclimate reconstruction and the positioning of the coral skeletal research.[1][2]

It is also an important issue to reconstruct the climate from the

Fig. 1 Massive colony of *Porites* (left) seen in the coral reef of Ishigaki Island, Ryukyu Islands and the x-ray positive photograph of a columnar sample (right)
In the x-ray photograph, the dark colored band corresponds to the high-density area, and the light colored band corresponds to the low-density area. One set of dark and light colored bands represents one annular ring.

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coral fossils from the Little Ice Age[Term 1] and the Medieval Warm Period, as well as the Holocene[Term 2] or the Pliocene[Term 3] Warm Period of 3.5 million years ago. The research method using the coral skeleton may also help clarify the coral bleaching events that are caused by abnormally high temperatures and ocean acidification phenomena.

In this paper, the research for reconstructing the past climate changes using the modern and fossil coral skeletons will be described, along with the examples of the latest research that is progressing through the combined evaluation of various indices, under the recent breakthroughs. Also, the methodology for enhancing the accuracy of global environment prediction will be discussed.

2 Knowing the temperature and salinity from the chemical composition of coral skeletons

Some of the massive colonies of the *Porites* corals that are distributed widely in the shallow waters of the tropical and subtropical zones continue to grow over the past several hundred years while secreting skeletons, whose main ingredient is calcium carbonate, at 1~2 cm thickness per year (Fig. 1). The skeletons consist of areas of high and low density layered on top of each other, and annular bands are thus normally formed. When a columnar sample is collected from a coral whose colony surface is alive, the year of skeleton formation can be known accurately by counting the annular bands. By cutting and analyzing the minute samples at 0.2~0.4 mm intervals along the growth axis of the skeleton, the paleoclimate can be constructed at high resolution of monthly or higher time units.

Oxygen isotope ratio is used frequently in the researches for the chemical composition of the coral skeletons. Normally, the oxygen isotope ratio is expressed as $\delta^{18}O$ by calculating the per mil (‰) of the isotope ratio in the sample ($^{18}O/^{16}O$) against the standard sample. The isotope ratio of oxygen in calcium carbonate and the isotope ratio of oxygen in seawater are given small letters c and w, and are expressed $\delta^{18}Oc$ and $\delta^{18}Ow$, respectively. The oxygen isotope ratio of calcium carbonate ($\delta^{18}Oc$) is dependent on the temperature when precipitation occurred and the oxygen isotope ratio of the seawater (correlated to salinity) (Fig. 4). To estimate the water temperature from the oxygen isotope ratio of the skeleton, it is preferable to use the relational expression obtained by comparing the oxygen isotope ratio of the upper part of the colony and the seawater temperature observation records. Also, to avoid the effect of skeletal growth rate on the chemical composition, the analysis should be done along the maximum growth axis of the colony where the growth rate is 5 mm y^{-1} or higher. In the area where the salinity variation is small throughout the year, the oxygen isotope

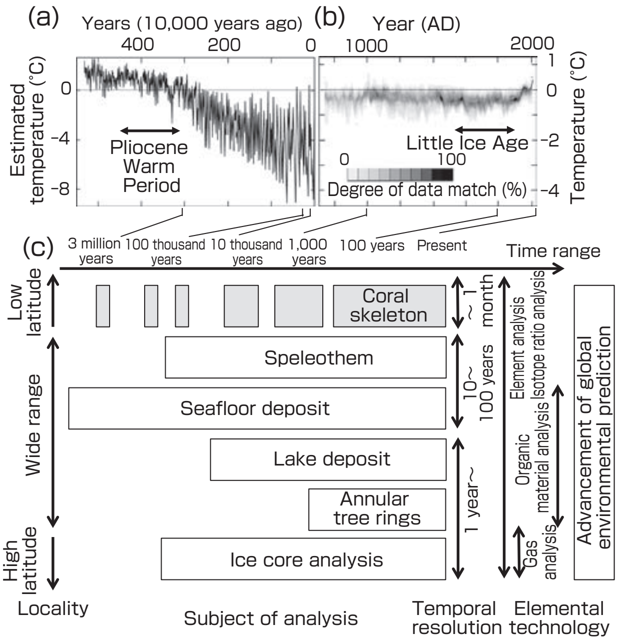

Fig. 2 Subject used in paleoclimate reconstruction and the positioning of coral skeletal research

(a) Estimation of temperature variation for the past 5.5 million years.[2] The past temperature can be estimated since the oxygen isotope ratio of the carbonate shell of the benthic foraminifers obtained from the core sample of deep seafloor deposits is a good index of global ice volume. It is an estimate of the temperature difference compared to present in the South Pole region, and the absolute value of the temperature difference differs greatly according to the latitudes and regions. (b) Temperature variation in the past 1200 years (from Fig. 6.10.c of Reference[1]). The deviation from the average value for 1961-1990 is shown and the degree of match among several researches is shown by darkness of color. (c) The producing range, analysis method, and temporal resolution of the subject used in the paleoclimate reconstruction using coral skeleton and others are presented schematically.

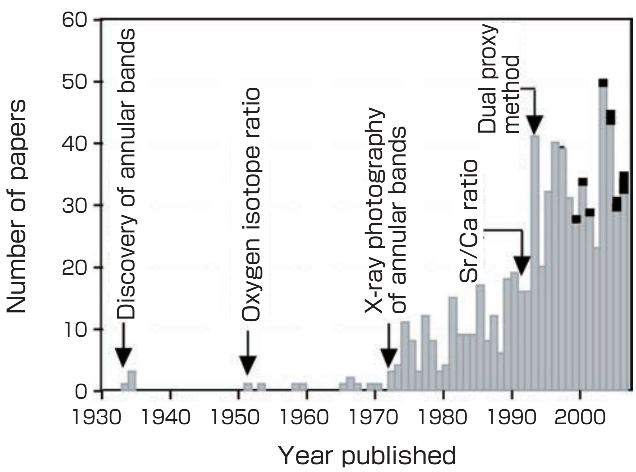

Fig. 3 Change in the number of papers on skeletal annular band of reef-building corals

From the number of papers listed in the Coral Banding Bibliography, AUSCORE on the website of the Australian Institute of Marine Science (http://www.aims.gov.au/pages/auscore/auscore-08.html). The papers contributed by AIST are marked as black bars.

ratio of the coral is a good index of the seawater temperature. For example, the oxygen isotope ratio of the corals from Ishigaki Island (Ishigaki-jima), the Ryukyu Islands corresponds well with the seawater temperature.[3]

For the coral skeletons, other useful indirect indices (proxies) have been found other than the oxygen isotope ratio. The strontium/calcium (Sr/Ca) ratio and uranium/calcium (U/Ca) ratio of the coral skeletons change according to seawater temperature only.

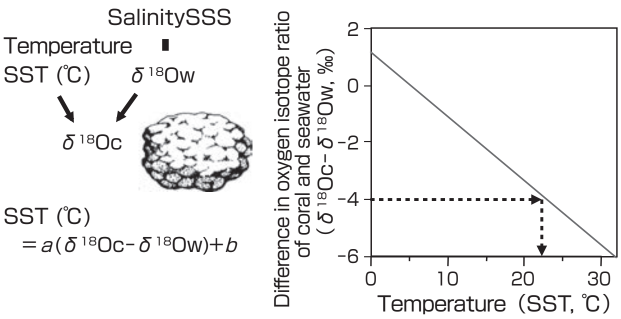

Fig. 4 Oxygen isotope ratio (δ18Oc) of the coral skeleton and sea surface temperature (SST)
The oxygen isotope ratio is expressed as $\delta^{18}O$ by calculating the per mil (‰) of the isotope ratio ($^{18}O/^{16}O$) in the sample against the standard sample. The oxygen isotope ratio in calcium carbonate is expressed with a small letter c. By calculating the relational expression by comparing the oxygen isotope ratio of the surface of the coral colony and the seawater temperature observation record, the seawater temperature at that time can be estimated from the oxygen isotope ratio of the past skeletons. Strictly speaking, it is affected by the oxygen isotope ratio of seawater ($\delta^{18}Ow$), but this can be neglected in the marine region with small variation in sea surface salinity (SSS). The salinity[Term 4] is expressed without units according to the convention of oceanography.

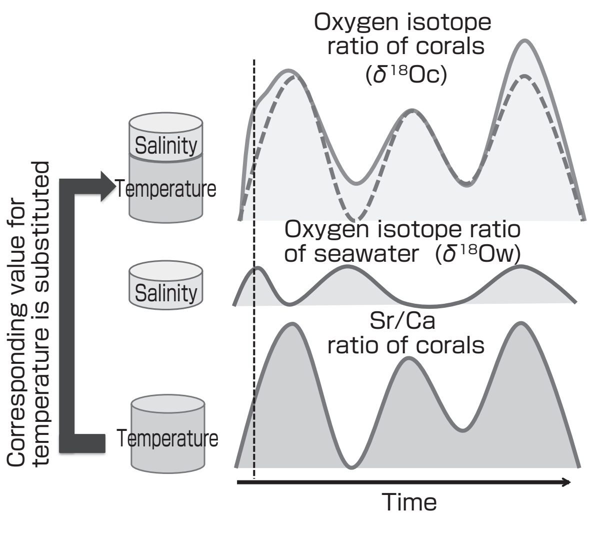

Fig. 5 Conceptual diagram of the dual proxy method using oxygen isotope ratio and Sr/Ca ratio of the coral skeleton
The reconstruction of the seasonal variation of temperature and salinity is presented.

The oxygen isotope ratio of coral skeletons is dependent on both the seawater temperature and salinity (more accurately, the oxygen isotope composition of seawater), while the Sr/Ca ratio is dependent only on temperature. Therefore, by estimating the temperature from the skeletal Sr/Ca ratio, and then subtracting the variation by temperature from the variation of the skeletal oxygen isotope ratio, the difference will indicate the variations of the oxygen isotope ratio composition of the seawater or the variations in salinity.[4] This is the dual proxy method using oxygen isotope ratio and Sr/Ca ratio of the coral skeleton (Fig. 5). The U/Ca ratio can also be used instead of Sr/Ca ratio.

3 Near past climate change in Ishigaki and Chichi Islands reconstructed from coral skeletons

The long-length coral research in the Northwestern Pacific region around Japan has not been done actively compared to overseas. Our research group conducts chemical analyses of the long columnar samples of *Porites* that are over 100 years old from Ishigaki Island (Ishigaki-jima,24° N, 124° E) of the Ryukyu Islands and Chichi Island (Chichijima, 27° N, 135° E) of the Ogasawara Islands (Fig. 6).

In the Pacific, a rapid change in the climate condition called the regime shift is known to occur,[5] and the event of 1988/1989 is notable in the Southern Ryukyus.[3] Before this regime shift, the seawater temperature during winter in the shallow waters of the coral reef of Ishigaki Island was sensitive to the Siberian High, and good correlation was seen with the monsoon index (pressure difference between Irkutsk and Nemuro) that indicates the strength of the monsoon. The

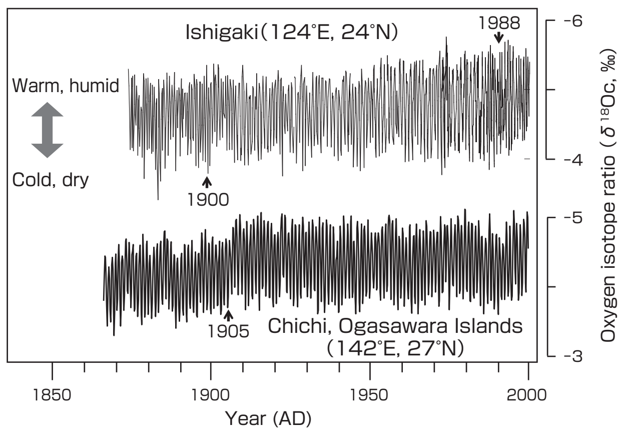

Fig. 6 Oxygen isotope ratio record of the coral skeletons collected from Ishigaki Island, Ryukyu Islands and Chichi Island, Ogasawara Islands[6][7]
The seasonal variations of temperature, etc. can be reconstructed at 1~2 month temporal resolution. The low temperature period at about 1900 for the Ishigaki coral discussed in this paper, the regime shift in 1988/89, and the salinity shift at around 1905 for the Ogasawara coral are marked with arrows.

oxygen isotope ratio of the Ishigaki coral skeletons in winter is determined by temperature, and the minimum winter temperatures reconstructed from the oxygen isotope ratio for 1971~1987 showed good correlation with the monsoon indices that express the strength of the seasonal winter winds. In contrast, the seawater temperature of Ishigaki after the regime shift decreased its correlation with the monsoon index. Instead the correlation with the southern oscillation index (SOI) became clearer than the monsoon index. This is an interesting phenomenon where Ishigaki that is categorized as the subtropical zone seemed to shift to the tropical zone. A period of low seawater temperature was observed in the coral sample from around 1900.[6] January 1902 was recorded as the winter with prevailing powerful Siberian Highs, and this was the year when the tragic incident occurred where the entire regiment of the Imperial Japanese Army was lost at Mt. Hakkoda during the winter training.

On the other hand, the reconstruction of temperature and salinity for about 130 years using the coral records at Ogasawara was the first true application of the dual proxy method[7] in the Northwestern Pacific region. For this coral sample, the U/Ca ratio, which is considered to be an excellent index of seawater temperature as in Sr/Ca ratio, was analyzed (Fig. 7). The good match of the reconstruction results of temperature and salinity by the combinations of oxygen isotope ratio and either the Sr/Ca or U/Ca ratio demonstrated the high reliability of the coral records (Fig. 8). The reconstructed seawater temperature corresponded with the Pacific Decadal Oscillation.[8] What was more interesting was that a rapid decline in salinity was observed around 1905-1910. The change in estimated salinity[Term 4] was about 1, and while the adequacy of scale remains under question, it was the most notable change in the coral records over 130 years. No sign such as diagenic alteration was observed in the skeleton during this period. The cause of salinity decrease at the beginning of the 20th century in Ogasawara was assumed to be caused by the decreased evaporation volume due to the weakening of the Ogasawara High caused by the decline of the westerlies at the time. The relationship with the low temperature event shown in the coral record of Ishigaki Island is also interesting.

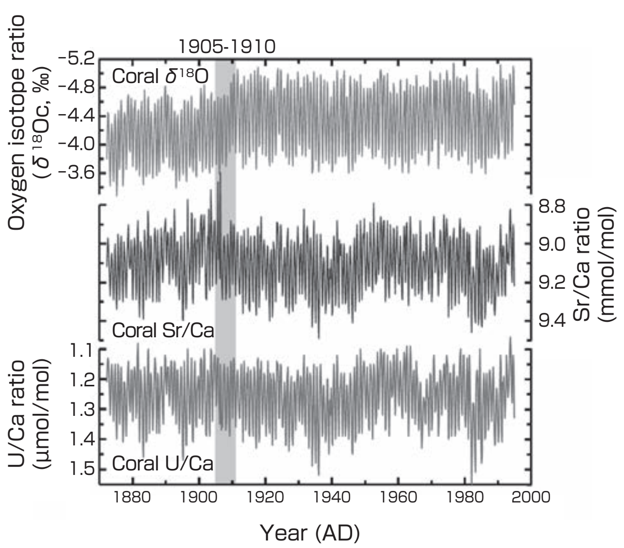

Fig. 7 Variation of oxygen isotope ratio, Sr/Ca ratio, and U/Ca ratio of the corals from Chichi Island, Ogasawara Islands[7]

The time from 1905 to 1910 when rapid increase in oxygen isotope ratio was seen is shaded.

4 Reconstruction of El Niño by fossil corals of the Pliocene Warm Period

El Niño phenomenon that occurs every few years in the equatorial Pacific region plays an important role in the current climatological system. With the progression of global warming, how will El Niño-Southern Oscillation (ENSO) change in the future? The *Fourth Assessment Report of the IPCC* predicts a frequent occurrence of powerful El Niños[9] but there is much opposition. The investigations of coral skeletons were conducted actively to address this issue.[1] Through the analysis of coral records over 500 years including the period before the Industrial Revolution, it was found that the strength of El Niño was correlated to the average seawater temperature, and El Niño was active as the temperature increased. This indicates that ENSO is affected by average global climate conditions, and implies the possibility that ENSO may change due to future warming. Also, correlation

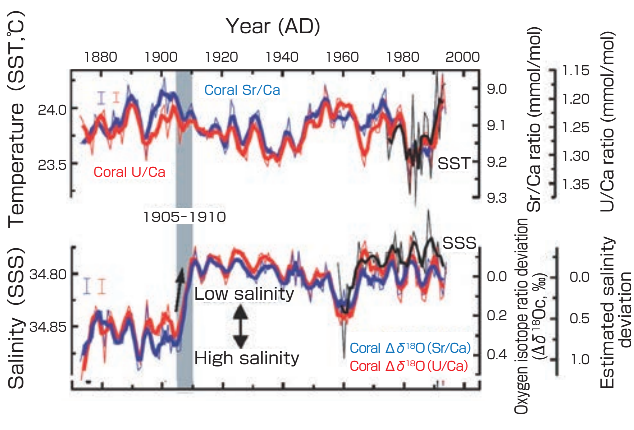

Fig. 8 Variations of sea surface temperature (SST) and sea surface salinity (SSS) reconstructed from the coral from Ogasawara Islands[7]

For salinity, the amount that contributed to the salinity variation of the oxygen isotope ratio calculated by dual proxy method from the coral skeleton is converted to salinity, by using the relationship of oxygen isotope ratio and salinity of the seawater in the Northwestern Pacific region (increase of salinity 1.0 equivalent to increase of oxygen isotope ratio 0.42 ‰). The deviation is labeled as estimated salinity deviation from the recent value (right axis). The results of the two combinations of oxygen isotope ratio with Sr/Ca ratio (blue line) and with U/Ca ratio (red line) are shown. The measured temperature and salinity are also shown (black line). The region of 1905 to 1910 when rapid decrease in salinity was observed is shaded.

was observed between the past seawater temperature and the strength of ENSO for the several warm periods observed during the Middle Holocene^Term 2 (about 6,000 years ago) and the Last Interglacial period (about 120 thousand years ago). These are in accord with the hypothesis that ENSO is affected by the average global climate conditions.

The Pliocene Warm Period at about 4.6 million to 3 million years ago is considered to be most similar to the climate condition that may be caused by global warming (Fig. 2a). Although the Jurassic and Cretaceous Periods of the Mesozoic Era,^Term 5 about one hundred million years ago when the dinosaurs existed, were also warm periods, the positions of the continents were totally different and simple comparison with the modern climate cannot be made. For the Pliocene Warm Period, a hypothesis has been proposed that the temperature gradient in the equatorial Pacific that caused El Niño disappeared, "permanent El Niño" where the seawater temperature of the entire region remained high occurred, and El Niño that occurred every few years ceased. On the other hand, there is a hypothesis that El Niño existed in the past, the temperature gradient between the east and west of Pacific increased, and El Niño occurred more powerfully and more frequently. The two hypotheses are based on the analysis of the core samples of the deep seafloor deposits with temporal resolution of several thousand years to several ten thousand years, and it was difficult to directly observe the El Niño phenomena that occur at several year intervals.

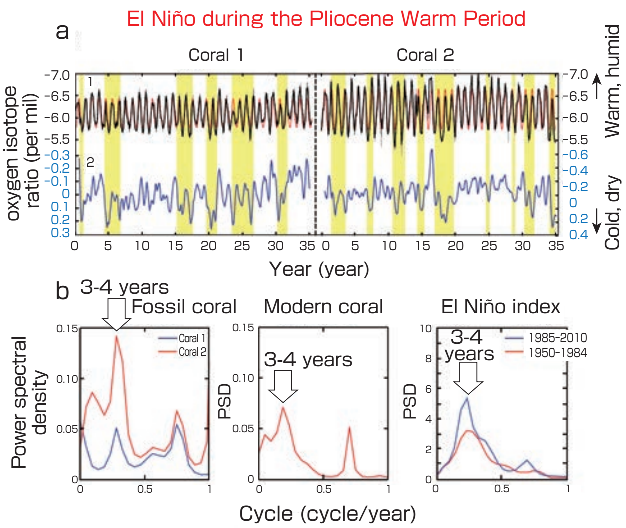

Fig. 9 (a) El Niño during the Pliocene Warm Period recorded in two fossil coral colonies[10]
This shows the annual variations for about 35 years for the two coral colonies (Coral 1 and Coral 2) in different periods about 3.5 million years ago. Black line is the variation of oxygen isotope ratio, red line is the seasonal pattern of average oxygen isotope ratio within the period, and blue line is the anomalies calculated by subtracting the average seasonal pattern from the oxygen isotope ratio variation. The period shaded by yellow color is estimated to be El Niño.
(b) Power spectral density[10]
The power spectral density shows at which cycle the variation is great in the chronological data, and offers a guideline for detecting the period variation ingredient. From left are the power spectral densities for oxygen isotope ratio of fossil corals (blue line = Coral 1; red line = Coral 2), oxygen isotope ratio of a modern coral, and El Niño index (Nino 3.4 index = anomalies for temperature of tropical Pacific; blue line = 1985~2010; red line = 1950~1984). There is a common peak at 0.3 cycle/year (3-4 year cycle).

The author's research group discovered well-preserved fossil corals from the strata that corresponded to the warm period in Luzon Island, the Philippines, and succeeded in analyzing and obtaining the record of seawater temperature variation that is the oldest direct evidence of El Niño.[10] The corals secrete aragonite skeleton, but with passage of time, this changes into stable calcite depending on the temperature and pressure conditions on the earth surface. Normally, after 100 thousand years, the production of unaltered coral fossils is extremely rare. However, in this stratum, the coral fossils are surrounded by mudstone that is an impermeable stratum, and this is effective in preserving the primary aragonite skeletons. The oxygen isotope ratio composition (index of temperature and salinity) was analyzed for the two colonies of coral fossils collected, and the seasonal variation of the atmosphere and marine environment for 70 years and the chronological variation patterns were extracted (Fig. 9a).

The marine region around the Philippines is strongly affected by El Niño, and it is known that the variation pattern of the oxygen isotope ratio of extant corals is an excellent record of the variation pattern of the current El Niño. When the results of analysis of the extant and fossil corals using the same method were compared, it became clear that the El Niño occurred at about the same cycle in the Pliocene Warm Period as the present (Fig. 9b).

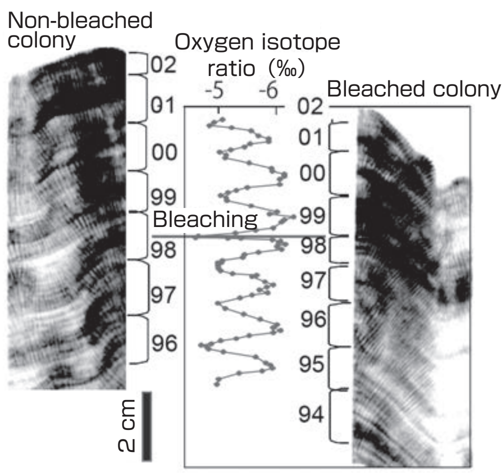

Fig. 10 Effect of large-scale bleaching event of August 1998 observed in the *Porites* skeleton of Ishigaki Island
The x-ray photograph of the skeletons of the bleached colonies and of those that did not undergo bleaching, and the oxygen isotope ratio profile along the growth axis of the bleached coral skeleton
The samples were collected in September 2002.

This result refutes the possibility of the permanent El Niño theory that states that El Niño will not occur in global warming which has been the major way of thinking. Also, it strongly indicates that El Niño will continue to persist on the warmed earth. This result will provide new hints to predict El Niño and its effects in the future global warming.

5 Coral bleaching phenomenon and decreased biological diversity of coral reef caused by abnormally high seawater temperatures

The coral bleaching phenomenon that occurred in the Great Barrier Reef of Australia in the southern hemisphere at the beginning of 1998 shifted to the northern hemisphere with the passage of seasons, and coral bleaching at a scale unseen before occurred in the coral reefs around the Ryukyu Islands in August 1998.[11] Although the biological and biochemical researches for coral bleaching were done actively particularly on the relationship between the coral and symbiotic algae, here, the focus will be on the coral skeletons. When the corals are bleached, what records are left in the skeletons?

In the coral reef off the coast of Yasurazaki in the east coast of Ishigaki Island, there is a massive colony consisting of three fused *Porites* colonies. It was observed that during the large-scale bleaching event in 1998, bleaching was seen in one colony while bleaching did not occur in the adjacent two colonies.[12] A jump that corresponded to the bleaching period was observed in the oxygen isotope ratio profile analyzed at high resolution along the growth axis of the skeleton, and this was interpreted as the halt of coral skeleton growth for a few months immediately after bleaching.[13] Columnar samples were collected again from these colonies in September 2002, four years after the large-scale bleaching event, and x-ray images were taken for observation. It can be seen that the growth speed significantly declined in the skeletons during 1998 only (Fig. 10). As the global warming progresses and high seawater temperatures occur frequently, the growth of coral skeletons is inhibited and the environment may become unsuitable for growth. On the other hand, if the high seawater temperature condition is resolved in a short time, some of the corals such as the *Porites* can recover from bleaching and may be able to survive. The evaluation of the effect of abnormally high temperatures on the coral and the coral reef ecosystem is an important research topic.

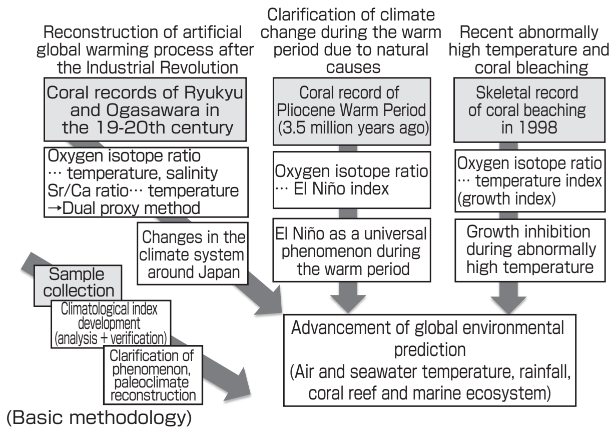

Fig. 11 Basic methodology of the coral skeletal climatology (lower left) and the development of three researches addressed in the paper

The meaning and interpretation of the indices used and the scenario of contribution to the final goal are presented for the three studies addressed in the paper, "Near past climate change of Ishigaki and Ogasawara reconstructed from coral skeleton," "Reconstruction of El Niño by fossil corals from the Pliocene Warm Period," and "Coral bleaching by abnormally high temperature."

6 Effect of marine acidification phenomenon on the coral reef

Marine acidification is recently gaining attention as a new global environmental issue.[14] The carbon dioxide released into the atmosphere by human activity migrates into the ocean to reduce the pH of seawater and the saturation of carbonates, and negatively affects the development of marine organisms and calcification of coral and foraminifers.[15][16] It is reported that in the skeletal analysis of the 328 colonies of *Porites* collected in 69 marine regions of the Great Barrier Reef, the calcification rate that had been stable for the past 400 years rapidly changed and decreased 14 % after 1990, and the relationship with marine acidification was indicated.[17] The boron isotope ratio (ratio of ^{11}B and ^{10}B) in the coral skeleton is an excellent index of seawater pH,[18] and the reconstruction of the changes in past seawater pH using the long-length coral samples and fossil corals is an important future topic of research. The analysis of boron isotope ratio is measured using the thermal ionization mass spectrometry (TIMS) or the multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS), and the introduction of such high-performance

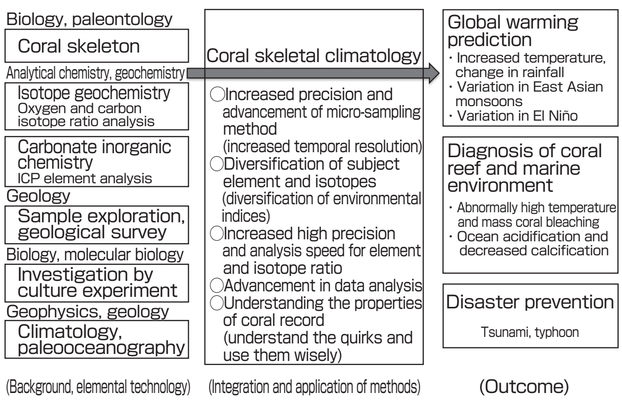

Fig. 12 Scheme of research development for coral skeletal climatology

This scheme shows the elemental technologies of the research, the basic fields, the integration of the methods that compose the body of the coral skeletal climatology and its application to the actual subject, and the social demands to which the outcome may contribute.

analysis devices is essential in the advancement of research.

7 Summary and future prospect

It was shown that the coral skeleton is excellent as a medium recording the past global climate changes, and that the attempts to read the record of climate change have advanced by using the state-of-the-art technology (Fig. 11). The necessity for coral skeleton research is expected to increase in the future as the global warming prediction becomes advanced. Also in the *Fourth Assessment Report of the IPCC*, the decrease in rainfall is predicted in the subtropical zone according to the climate model, but its accuracy must be raised.[9] The reconstruction of the past salinity oscillation that is closely related to rainfall, along with seawater temperature, is an immediate concern. This can be met by the composite index method using oxygen isotope ratio and Sr/Ca ratio as exemplified by the coral skeletons of Ogasawara. This method can be applied to fossil corals, and there is an example of investigation of coral fossils from the last ice age in the East China Sea.[19] The *Fifth Assessment Report of the IPCC* is scheduled for publication around 2013. Until then, it is necessary to promote the pH reconstruction by boron isotope ratio analysis and the analysis of climate change by the dual proxy method of oxygen isotope ratio and Sr/Ca ratio, and to reflect the results in the *Fifth Assessment Report*. Therefore, further promotion of coral skeletal climatology is needed.

On the other hand, there are points that need to be clarified, such as the basic mechanism of why the climatological factors such as seawater temperature are recorded in the chemical and isotope compositions of the coral skeletons.[20] In addition to the geochemical methods, it is necessary to conduct culture experiments[21][22] and molecular biological methods[23] to clarify the biological mechanism. The researches that transcend the conventional disciplines may allow application to the prediction and evaluation of calcification inhibition of marine organisms that may be caused by the future marine acidification (Fig. 12).

The 2011 off the Pacific coast of Tohoku Earthquake (Great East Japan Earthquake) occurred on March 11, 2011, and major damages occurred due to the tsunami to the Pacific coast of the Tohoku and Kanto regions. The re-evaluation of the past tsunami damages throughout Japan is an urgent issue. Particularly, the tsunamis of the Jogan Earthquake that struck the Tohoku region in 869 and of the Meiwa Earthquake that occurred in the South Ryukyu region in 1771 are gathering attention due to the similarities to the earthquake in 2011, in the height of the tsunami and the scale of casualties. The methods of coral skeletal climatology can be applied to disaster research by looking at the *Porites* boulders pushed ashore by the tsunami. The author's research group applied the radiocarbon dating method and the coral skeletal climatology method to the *Porites* boulders scattered on the east coast of Ishigaki Island, Southern Ryukyu, and demonstrated that these were washed ashore by the Meiwa tsunami.[24][25] The contribution to the research on the Meiwa tsunami, which was a historical earthquake-caused tsunami in the Okinawa region, has high social demand from the perspective of regional disaster prevention.

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Terminology

Term 1: Little Ice Age: the period of cold climate that occurred from about the mid 14th century to the mid 19th century. Concerning the degree of temperature decrease and regions, there is much that remains unknown.

Term 2: Holocene: the most recent of the geological time divisions (epoch) and includes the present age. It covers from about 10 thousand years ago when the last ice age ended to present.

Term 3: Pliocene: one of the geologic epochs of the Cenozoic Era. It covers the period from about 5 million years ago to about 2.58 million years ago. The first humans such as Australopithecines appeared during this epoch.

Term 4: Salinity: there is a long history of revisions of the analysis methods and expressions of the salinity of seawater.[26] "Practical salinity" was defined as the salinity measurement of seawater using electric conductivity became common, but this value is based on the conductivity ratio of the standard seawater and sample water, and is given no unit.[27] This expression is used widely to present. Recently, to precisely calculate the physical quantities such as the density of seawater from salinity, "absolute salinity," in which the weight of the dissolved matter is assessed accurately, had been proposed, and this is given the unit g kg^{-1}.[28] The conversion equation from "practical salinity" to "absolute salinity" has also been proposed. In this paper, practical salinity will be called salinity and handled as a quantity without unit.

Term 5: Mesozoic Era: a geological time between the Paleozoic and the Cenozoic Eras. It started about 250 million years ago and lasted till about 65 million years ago. The Mesozoic is composed of the Triassic, Jurassic, and Cretaceous Periods. This was the age of the dinosaurs.

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Discussions with Reviewers

1 Overall comment (1)

Comment (Shigeko Togashi, AIST)

This paper evaluates the effect of climate change caused by human activities necessary for the realization of sustainable society. To increase the prediction precision of the future, the paper shows that breakthroughs occur by the introduction of new geochemical indices in the analysis of past climate change left in the coral skeletons. The future direction is stated, and I think it is appropriate as a *Synthesiology* paper.

Please provide a diagram of outline that shows other topics in paleoclimatology addressed in IPCC, and indicate where the coral skeleton research is positioned in that realm. I also think you should clarify the relationships between the factors of climate change and the indices that comprise the elemental technologies to analyze those factors.

Answer (Atsushi Suzuki)

I added Fig. 2 to explain the various subjects used in the paleoclimate reconstruction and the positioning of the coral skeleton research. I also summarized the research materials and analysis methods used in paleoclimate reconstruction, other than those concerned with coral skeletons. I presented the reconstructed map of temperature (seawater temperature) for the entire targeted geologic time, and attempted to present the overall trend.

2 Overall comment (2)

Comment (Koh Naito, Center for Service Research, AIST)

This paper presents a synthetic approach that attempts a multifaceted modeling of a complex natural phenomenon by combining the data of careful chemical analysis. This approach is new, and in particular, the attempts to understand quantitatively the natural phenomenon, which used to be modeled qualitatively, was only started in the 1990s. I think this approach is expected to contribute greatly to the future society. In that sense, this area of study is highly interesting to the researchers and practitioners outside the geoscience field. Therefore, your effort of trying to use as few technical terms as possible greatly helps the readers.

In that sense, please create a table that provides supplementary explanation for the geologic time categories such as “Pliocene,” “Holocene,” “Mesozoic,” “Jurassic,” or “Little Ice Age,” to enhance understanding by the readers outside the field.

Answer (Atsushi Suzuki)

For the geological time category, I created a terminology section at the end of the paper to provide supplementary explanation. I added the descriptions in the text for “Little Ice Age,” “Holocene,” “Pliocene,” and “Mesozoic.”

3 Composition as a *Synthesiology* paper

Comment (Koh Naito)

To enhance overall understanding, I recommend that you create a single diagram that shows what the data used in the paper mean and their correlations, and add this to the end of the paper. Although the reader can understood the points as one reads through the paper, it will help the reader outside the field to read through and then review the overall argument and structure using such a diagram at the end.

Answer (Atsushi Suzuki)

I added new diagrams in the revision.

Figure 11 is an attempt to present the meaning and interpretation as well as the correlations of the data of the three studies addressed in the paper, “Near past climate change of Ishigaki and Ogasawara reconstructed from coral skeleton,” “Reconstruction of El Niño by fossil corals from the Pliocene Warm Period,” and “Coral bleaching by abnormally high seawater phenomenon." Figure 12 is a table that summarizes the scheme of the research development of coral skeletal climatology. I hope Figs. 11 and 12 will allow the readers to overview the overall structure of the coral skeletal climatology on which we are currently working.

4 Emphasis on the composite evaluation of various indices

Comment (Koh Naito)

When one reads your discussion, the understanding of the natural phenomenon is emphasized. To clarify the synthesiology as an integrated approach, I think you should emphasize the importance of accurately understanding the phenomenon by composite evaluation of various indices that you mentioned in the summarizing chapter.

Answer (Atsushi Suzuki)

As you mentioned, it is extremely important to evaluate the indices with advantages and disadvantages in a composite and integrated manner and to accurately reconstruct the past climates, in the paleoclimate reconstruction by geochemical method using coral skeletons. I emphasized this point in the introduction and the discussion.

5 Breakthroughs by the introduction of new geochemical index

Question (Shigeko Togashi)

The former Fig. 2 is a citation of AUSCORE, and I think it is a good graph that shows how breakthroughs occur by the introduction of new geochemical index. Can you add the contributions of the AIST research groups to this graph?

Answer (Atsushi Suzuki)

In the revision, former Fig. 2 became Fig. 3. I altered the histogram to show the papers of the AIST research groups.

6 Scale of past temperature variations recorded in the fossil corals

Comment (Shigeko Togashi)

To clarify the breadth of the past time scale, please show the approximate temperature changes after the Pliocene, where the observation of the temperature variations recorded in the modern corals can be applied to fossil corals.

Answer (Atsushi Suzuki)

I added the reconstruction diagram of the temperature for the entire geological time scale after Pliocene to the newly added Fig. 2a, and attempted to show the overall trend in an easily understandable manner. This temperature reconstruction was done by estimating the temperature differences with the current temperatures in the South Pole region, based on the oxygen isotope ratio of the carbonate shell of the benthic foraminifers obtained from the core samples of deep seafloor deposits. Therefore, please note that the absolute value of the temperature differences may differ greatly according to latitudes and regions.