Recent remarkable decrease of dissolved oxygen of the Japan Sea Proper Water in the northeastern Japan Basin

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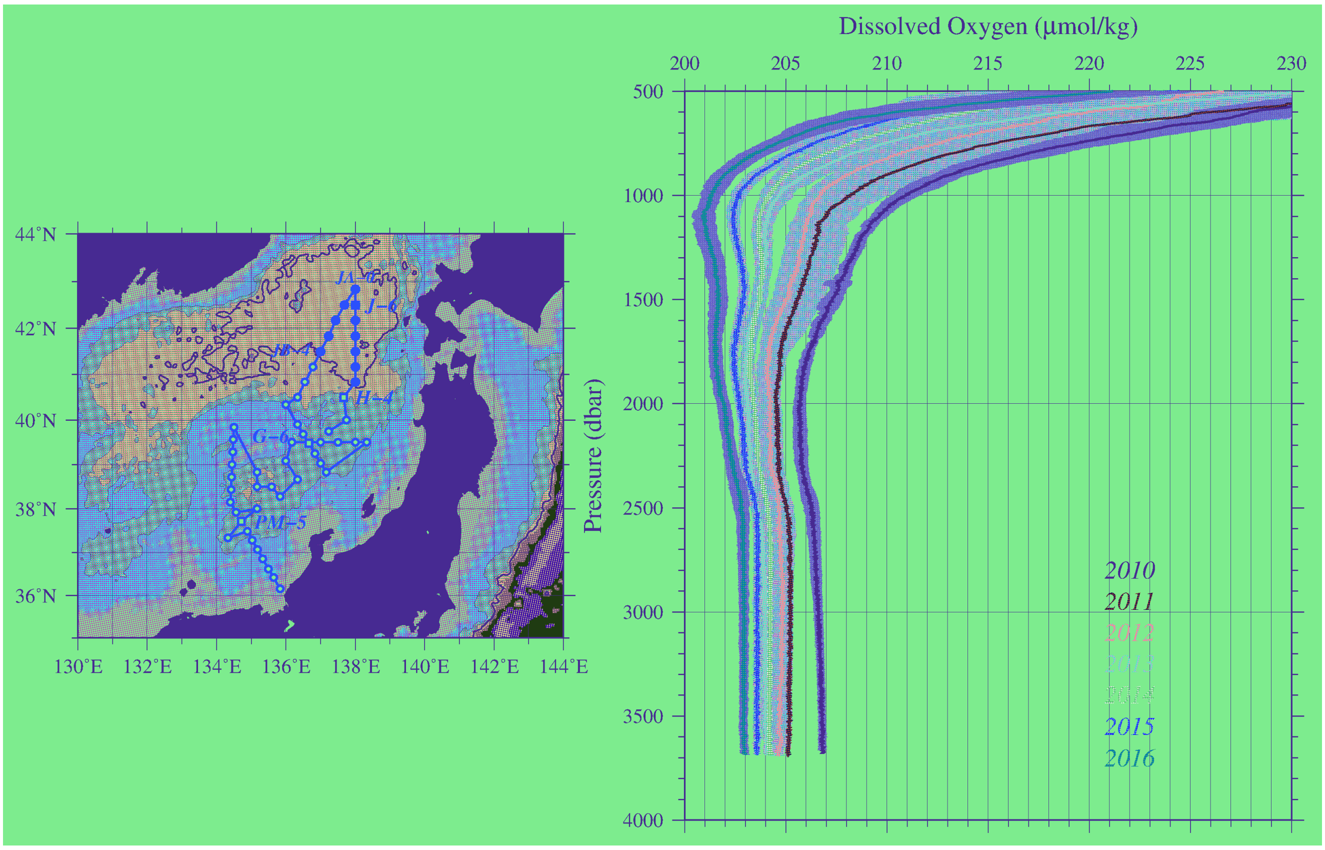
The Japan Sea is a marginal and semi-closed sea located on the western North Pacific. Below about 300m depth is occupied by a relatively uniform water mass, and Uda (1934) named this water mass as the "Japan Sea Proper Water (JSPW)". Hydrographic observations since 1950’s have revealed gradual increase of potential temperature and decrease of dissolved oxygen (DO) (e.g. Gamo et al, 1986; Minami et al., 1999). The cause of this warming and deoxygenation is considered to be weakening of winter cooling associated with the climate change in the northwestern region of the Japan Sea where the JSPW is formed. In this study, we investigated the temporal change of the JSPW in the northeastern Japan Basin where the depth exceeds 3500m, using the high quality hydrographic data obtained during the period of 2010 to 2016. The vertical profile of potential temperature and DO averaged over the Basin consists of three water masses, i.e., the “Bottom Water” of JSPW below 2500m depth, the "Deep Water" of JSPW between 2500m and 1000m depth, and the "Upper JSPW" between 1000m depth up to the thermocline. The Bottom Water is mostly uniform in both potential temperature and DO, and warmed by about 0.1C and deoxygenated by about -3.7 umol/kg during the period. In the Deep Water, potential temperature gradually increases upwards, while DO reaches its minimum at around 2000m depth and turns to increase above it. In the Upper JSPW, both potential temperature and DO show much larger upward increase compared with in the Deep Water. It is noted that temporal decrease of DO in the Upper JPSW between 1000m and 500m depths is about 10-18 umol/kg. This decreasing speed is larger than that in the upper part of the Deep Water. Consequently, another DO minimum layer became apparent since 2013 at about 1000m depth, the boundary between the Upper JSPW and the Deep Water. In contrast, the potential temperature in the Upper JSPW warmed by about 0.1C, which is the same as in the Deep and Bottom Waters. In the Yamato basin, warming and decrease in dissolved oxygen are progressing as well, but no remarkable DO minimum layer could been seen. Several mechanisms are plausible and will be discussed to account for the complicated including double minimum DO layers, such as 1) decrease in the oxygen saturation by warming SST, 2) decrease of the JSPW formation and weakening of deep convection, 3) change of the mixing rate with low DO and rich nutrients waters, and 4) increase in consumption of DO associated with biological activity.

Keywords: northeastern region of Japan Basin, Japan Sea Proper Water, decreasing of dissolved oxygen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Vertical profile of dissolved oxygen in the eastern Japan Basin, Yamato Basin, and Tsushima Basin of the Japan Sea in 2016

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The Japan Sea is a semi-closed marginal sea in the North Pacific Ocean. Dissolved oxygen concentration in deep water of the Japan Sea, however, is higher than that of the adjacent North Pacific Ocean due to its independent deep-ventilation. Gamo (1999) found that dissolved oxygen in bottom water deeper than 2000 m depth in the eastern Japan and Yamato Basins continuously decreased during the last 50 years at about 0.8 μmol/kg/year of consumption rate. This long-term trend of decrease could be derived from stagnation in the deep ventilation which associates with warming in the northern part of the Japan Sea including coastal area of Siberia. Kumamoto et al. (2008) found temporary increases on the long-term decrease trend and proposed a hypothesis: “Dissolved oxygen is supplied to the bottom water in the western Japan Basin due to new bottom water formation only in severe winters. Oxygen-rich new bottom water is transported to the Yamato and eastern Japan Basins within a few years along an anti-clockwise deep current in the Japan Sea. Without the oxygen supply the concentration in the bottom water decreases due to consumption for decomposition of organic matter”. Based on this hypothesis, Kumamoto (2010) speculated that “true” consumption rate of dissolved oxygen in the bottom water is about 2 μmol/kg/year and the bottom water of the Japan Sea will become anoxic within 100 years. Here we measured vertical profile of dissolved oxygen in the eastern Japan Basin, Yamato Basin, and Tsushima Basin of the Japan Sea in 2016 and discussed temporal change in oxygen concentration in the bottom water in the past several years. During research cruises of Oshoro-maru-26th (July 2016), KIOST-Eardo (September 2016), and Nagasaki-maru-447th (October 2016), dissolved oxygen concentration from surface to bottom was measured on board using modified Winkler method. Uncertainty in oxygen measurement was estimated to be about 0.2 μmol/kg from replicate measurements. The vertical profiles of dissolved oxygen observed in 2016 were compared with those measured in 2010. Between 2010 and 2016, dissolved oxygen concentration in the bottom water of the three basins decreased about 5 μmol/kg in average and consumption rate was calculated to be about 0.8 μmol/kg/year, which agrees with that observed during the last 50 years. According to Kumamoto (2010), during the past six years dissolved oxygen concentration in the bottom water should decrease more than 10 μmol/kg if there was no oxygen supply due to formation of new bottom water. Although these observational results imply supply of dissolved oxygen into the bottom water between 2010 and 2016, dissolved oxygen concentration in the bottom water in the eastern Japan Basin monotonously decreased from 2010 and 2016 (JMA, 2016). This discrepancy could be resolved by decrease in organic matter flux from surface to bottom waters and/or increase in circulation rate of the deep current of Japan Sea. We will continue observations, including primary production and direct measurement of the deep current, in the Japan Sea in 2017 and 2018 and discuss further these results. This work was supported by Environment Research and Technology Development Fund (ERTDF), the Ministry of the Environment, No. A-1002 “Mechanism elucidation and future forecast on the decreasing trend of dissolved oxygen concentrations in the deep water of the Japan Sea (2010-2012)” and No. 2-1604 “Global warming impacts on thermohaline circulation and subsequent biogeochemical change in the Japan Sea (2016-2018)”.

Keywords: Japan Sea Bottom Water, dissolved oxygen, global warming

Chlorofluorocarbons indicating the sudden weakening of the thermohaline circulation in the Japan Sea

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In the Japan Sea, there is independent thermohaline circulation: the origin of the deep water is the surface water in the northern Japan Sea because the surface water in winter due to evaporation and freezing is dense enough to sink toward bottom. Therefore, the deep water of the Japan Sea is lower temperature and higher dissolved oxygen than that of the adjacent North Pacific Ocean. The long time-series datasets of water temperature and dissolved oxygen in the deep water of the Japan Sea suggest that the thermohaline circulation in the sea had been weakening due to the global warming in recent decades. The production of chlorofluorocarbons (CFCs: CFC-11, CFC-12 and CFC-113 in this study) began in the 1930s and atmospheric CFCs had increased sharply since the 1960s. CFCs enter the ocean via air-sea gas exchange and do not hydrolyze in seawater. When surface water sinks into deep water by active thermohaline circulation, CFCs concentration of deep water was rewritten by mixing with surface water having high CFCs. Therefore, CFCs of the deep water at present has recorded the information of thermohaline circulation since the 1930s. In June 2011 and October 2012, we obtained vertical CFCs profiles in the eastern Japan Basin and Yamato Basin. The CFCs decreased with depth until above 2200m and then were almost constant at all stations. Therefore, the bottom water was defined as water below 2200m in this study. Although the CFC-11 and CFC-12 of the bottom water in the Yamato Basin were about 1.6 and 1.8 times higher than the Japan Basin, respectively, the CFC-113 was only 1.2 times. Apparent age of the bottom water calculated by CFC-12/CFC-11 ratio showed almost the 1960s regardless of area. If surface water sinking into the bottom water by the thermohaline circulation occurs in a similar scale every winter, the apparent age should show more recent age because atmospheric CFC-11 and CFC-12 had increased sharply since the 1960s. The result suggests that the sinking of surface water had hardly occurred after the 1960s. On the other hand, apparent age of CFC-12/CFC-113 ratio in the bottom water showed almost the 1980s regardless of area. Because CFC-113 has been released in atmosphere since the early 1960s, the result indicates that surface water sinking into the bottom water had occurred even after the early 1970s. These different results may depend on the follows: time history of each CFC in the atmosphere is different and the scale of thermohaline circulation had been changed after the 1970s. We estimate the deep and bottom waters formation rates from 1930 to 2011 at the Japan and Yamato Basins by using simple box model with CFCs. The estimation period is divided into old period from 1930 to 1975 and new period from 1976 to 2011 in consideration of atmospheric CFC-113 time history. The formation rates after 1975 have decreased by 21-30% in the deep water and 15-41% in the bottom water compared with those before 1975. There is no doubt the deep ventilation in the Japan Sea after 1975 has slowed down at least less than half that before 1975. Comparing the effect between the study area, the decrease in formation rate in the Yamato Basin are greater than that in the Japan Basin. These results may suggest that the dynamics of the deep and bottom waters formation, such as the route of deep circulation, had been changed by the sudden weakening of the thermohaline circulation after 1975. This work was supported by Environment Research and Technology Development Fund (ERTDF), the Ministry of the Environment, No. A-1002 “Mechanism elucidation and future forecast on the decreasing trend of dissolved oxygen concentrations in the deep water of the Japan Sea (2010-2012)” and No. 2-1604 “Global warming impacts on thermohaline circulation and subsequent biogeochemical change in the Japan Sea (2016-2018)”.

Keywords: Japan Sea, Chlorofluorocarbons, Thermohaline circulation, Global warming

Ocean acidification detected in coastal water around Japan

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Ocean acidification causes significant damages on marine ecosystems in polar regions and coral reefs etc., together with global warming. Japan Ministry of Environment has conducted measurements of hydrogen ion concentration, pH in about 2100 fixed stations covering the whole of coastal area in Japan since 1987, in the monitoring program to monitor quality of water pollution. In this study, by using these data, situations of ocean acidification in coastal waters in Japan were examined, which have been difficult to understand in detail so far.

Apparent 368 acidification and 18 alkalization trends were detected. Among them, 78 acidification and 13 alkalization trends were statistically significant. Progressing speed of ocean acidification in coastal waters is averagely at -0.0015 pH/yr, which is comparable to the estimates at the other fixed monitoring stations in open ocean, such as JMA 137E line, BATS and HOT program stations. Some industrial port sites including Ishinomaki in Miyagi, Tomakomai in Hokkaido and Tokyo Bay in Tokyo prefectures show 10 times as fast progressing speed as the average. We would clarify the mechanisms of the differences among local regions, and possible influences on marine ecosystems, in future study.

Our talk will also provide a tendency of ocean acidification/alkalization in each prefecture, and a diagnostic estimation of aragonite saturation rate (Ω_{AR}) to see an influence on crustacean in present.

Keywords: Ocean acidification , pH , Coastal water in Japan

Effects of ocean acidification on growth and calcification in juvenile Japanese surf clam *Pseudocardium sachalinense*

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Many previous studies have reported that ocean acidification could give negative influences on marine calcifiers. However, the influences of ocean acidification on edible marine species, especially on cold-water species, are poorly understood. Juvenile Japanese surf clam was exposed to five levels of pCO_2 (400, 600, 800, 1,000, and 1,200 μatm) during 20 weeks and these effects on its growth and stable isotope compositions of shell were examined. The clam is important in local fisheries and inhabits on the upper subtidal sandy bottom in northern Japan.

We found non-significant effects of elevated CO_2 on weight (whole body, shell, and soft tissue), shell length, shell width, and shell height during experiments. Meanwhile, shell thickness at a region that grew during experiments thinned in a pCO_2-dependent manner. These results suggest that effect of ocean acidification on juvenile Japanese surf clam was not the shell dissolution but the inhibition of shell formation.

We studied the contribution of acidified seawater on shell calcification by stable carbon isotope composition ($\delta^{13}C$). The $\delta^{13}C$ of the shells collected from the external margin of the outer shell layer showed significant positive correlations with pH ($R = 0.56$, $p < 0.05$). The regression slope of the relationship between shell $\delta^{13}C$ and pH was roughly the same as that between $\delta^{13}C$ of dissolved inorganic carbon (DIC) of seawater and pH, and calcification of the experimental specimens might be strongly affected by acidified seawater. Thus, by measuring $\delta^{13}C$ of molluscan shell and DIC of seawater, it might be possible to estimate the contribution of acidified seawater to calcification.

The concentration of carbonate ion which is necessary for calcification decreased with increasing pCO_2. Because of the influx of acidified seawater into the extrapallial fluid, the decrease in carbonate ion in the extrapallial fluid might induce a thinner shell formation. Therefore, in acidified seawater, Japanese surf clam might have a poor pH regulation of the extrapallial fluid.

Keywords: ocean acidification, growth effect, calcification, stable carbon isotope, Japanese surf clam

Anticipated impacts of ocean acidification on local societies in Japan

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Ocean acidification is anticipated to affect marine ecosystem services and human activities such as fisheries, aquaculture, tourism and recreation. However, extent of the impacts is expected to differ spatially. Thus ocean acidification may widen regional gaps of economic conditions and pose a social security threat in future by damaging specific local industries. Things might be further complicated because suitable habitats for the calcifiers, such as corals, scallops, oysters, pearls and shrimps, are projected to become sandwiched between migrating northern and southern limits regulated by ocean warming and acidification, respectively. Considering such backgrounds, this study aims to call for stakeholders' attention to the possible impacts of ocean acidification on local societies in Japan by sharing fundamental scientific knowledge through everyone's common interests: economic values.

Change in economic values of Japanese coral reefs was calculated by the product of changes in the area and health condition of coral reefs. The area was assumed to be regulated by annual maximum and minimum water temperature and minimum saturation state of aragonite (Ω_{arg}) (Yara et al., 2012; 2016). The health condition was assumed to be deteriorated by 15% per Ω_{arg} (Chan and Connolly, 2013; van Hooidonk et al., 2004). The change in economic values of Japanese fisheries and aquaculture was assumed to decrease by 10 through 40% per one pH unit of the water (Wootton et al., 2008).

Currently, calcifiers account for one-fifth of total fish catch in Japan (Ministry of Agriculture, Forestry and Fisheries, 2015). The annual economic values of tourism and fisheries profited by calcifiers in Japan were estimated to be 14,107 and 779-2,399 million USD, respectively (Cesar et al., 2003; Ministry of Environment, 2010).

The economic values of Japanese coral reefs were projected to increase by mid-century because of expansion of coral reefs in response to ocean warming (Figure 1). However, the economic value will decrease dramatically in the latter half of the century, due to possible extinction of coral reefs caused coral bleaching and ocean acidification. As a result, the total loss of economic values of Japanese coral reefs in this century was estimated to be 22-67 billion USD for tourism and 5-6 billion USD for fisheries by the end of the century.

Likewise, the total economic loss of Japanese fisheries by ocean acidification was estimated to be 15-37 billion USD by the end of the century. However, the impacts of ocean acidification are considered to be spatially different. For example, it is more concerned that the impacts on local industries are relatively prominent in such prefectures as Hiroshima, Okayama, Hokkaido, Fukui and Aichi where calcifiers currently account for the local fish catch by more than 30%.

It is obvious that global mitigation of ocean acidification such as reducing CO_2 emissions is essential to alleviate the impacts of ocean acidification. On the other hand, adaptive strategies would also be needed for aquaculture of calcifiers, which are very important for the local industries. Such strategies will only be achieved after consensus building among various stakeholders including citizens, policy makers and both natural and social scientists.

Keywords: Ocean acidification, Local society, Mitigation, Adaptation

Spacio-temporal variation of the increasing rate of pCO_2 in Kuroshio shelf-slope area

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We investigated spacio-temporal variation of the increasing rate of pCO_2 within the summer season in the Kuroshio shelf-slope area, one of the largest transition waters between western boundary current and coast in Japan. Study area was set as 137E-140E and north of 34N (to coastline), and 4057 historical pCO_2 data observed on July, August and September from 1995 to 2015 in this area was extracted from SOCAT ver.4 database. Interannual variation of water temperature within the dataset was examined as well as salinity, and as this result, it was recognized that the following four temperature-salinity domains have been emerged constantly within the study area thought the whole study period.
LTLS: 24C<T<26C and 33.0<S<33.5
LTHS: 24C<T<26C and 34.0<S<34.5
HTLS: 26C<T<28C and 33.0<S<33.5
HTHS: 26C<T<28C and 34.0<S<34.5
Interannual variation of pCO_2 within each temperature-salinity domain was then examined. HTLS, and HTHS and LTHS showed positive linear trend of pCO_2 with the same increasing rate of +1.9±0.3ppm/y, which value was slightly higher than that observed by Ishii et al. (2014) in the time-series station of 34N, 138E. However, linear trend of pCO_2 in LTLS showed significantly higher increasing rate than other three domains, +2.8±0.5ppm/y. Detailed analysis indicated that LTHS and HTHS roughly correspond to the data observed in the offshore side of Kuroshio current in July and August, respectively, while LTLS and HTLS roughly correspond to those observed in the shelf-slope area in July and August, respectively. The observed results indicate that the increasing rate of pCO_2 in the Kuroshio shelf-slope area varies even within the summer season, reflecting wide spacio-tenporal variation of water properties caused by complex biogeochemical processes in this quasi-coastal area.

Keywords: coastal region, global warming, pCO2

Intermediate-water acidification and biologic responses of planktic foraminifera

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Anthropogenic CO_2 emission is making lower pH conditions in the ocean, thereby marine organisms will be affected severely to their ecology and physiology. Recent studies suggest that large changes of pH in intermediate water of the Atlantic Ocean and indicates ocean acidification enhances during past two decades. More recently, similar lowering pH in intermediate water had reported in the North Pacific, but such studies are very limited. To confirm the progress of intermediate water acidification, we started to investigate carbonate chemistry of intermediate water and its biological responses in the North Pacific.
As a preliminary result in this study, we show the spatial distribution and morphological features of one planktic foraminiferal species *Globorotalia scitula* (Brady) which lives in the intermediate water on the monitoring line near Hokkaido Island (A-line) of Japan Fisheries Research and Education Agency (JFR). We performed the MOCNESS plankton towing on July 2016 and collected planktic foraminifers from each layer above 1,000 m water depth. *Globorotalia scitula* (Brady), the one of the deepest habitat species in planktic foraminifers is considered the environmental indicator of intermediate water, therefore we choose this species for evaluating biological responses. Vertical distributions of this species indicated remarkable bimodal distribution patterns in the water column. Maximum numbers of adult and juvenile specimens occurred at water density (sigma θ) = 26.9 (ca. 300 m) and 27.2 (ca. 500 m), respectively. In other words, juveniles lived in deeper water depth than adult ones. Such habitat depth is unique in the whole planktic foraminiferal life and indicates different habitat compared to other surface-dwelled planktic foraminifers.
We also performed the analysis of individual shell density of *G. scitula* by using Microfocus X-ray Computed Tomography (MXCT). Shell density variations of each specimens had wider ranges and those were equal to ca. 2.1 ~ 2.5 ug/um3. Shell density of *G. scitula* did not show remarkable differences with the water depth. It suggests that shell density of *G. scitula* did not change in the water column if the carbonate saturation (Omega_calcite) of ambient seawater was less than 1.0. In this presentation, we will show the pore density of *G. scitula* and discuss the relationships with carbonate chemistry.

Keywords: Ocean Acidification , Planktic foraminifera, Shell density analysis, Intermediate water

Study of the influence of long-term ocean acidification on underwater sound wave propagation

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Absorption loss (α) is a key factor in sound wave propagation through seawater. It is known that α decreases with rising seawater temperature and decreasing pH, but the full implications of recent global changes in marine environments have yet to be explored. Current reports show that both seawater temperatures and anthropogenic atmospheric CO_2 levels are increasing rapidly. Dissolved atmospheric CO_2 causes a decrease in seawater pH (marine acidification). Here, we present a study of long-term changes in the value of α, using observational temperature and pH data from the Pacific Ocean off the Japanese coast. We find that α decreased steadily over the past 30 years, with the most rapid decrease seen at high latitudes. In addition, we produce predicted values of α for 2100, based on two ocean acidification model scenarios. We also calculate the impact of decreasing values of α on submarine noise levels from long-term off-shore installations. We find that predicted noise levels increased by a factor of up to 1.44 between 2014 and 2100, a level of increase that could have a significant impact on marine mammals and sonar technologies. Our results highlight the importance of considering noise reduction techniques for future long-term off-shore installations.

Keywords: underwater sound wave propagation, absorption loss (α), pH, underwater noise level, long-term change

The dynamics of pore water in subsurface sediments at the site of controlled CO_2 release experiment

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Carbon capture and storage (CCS) in sub-seabed geological formations is a mitigation strategy that can aid the reduction of anthropogenic CO_2 emissions. In 2012, the QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage) project was undertaken by researchers from the UK and Japan. The project conducted a field-scale controlled CO_2 release experiment in order to examine the impacts on the marine ecosystem and evaluate the methods for detection and impact monitoring, should CO_2 leakage occur. Changes in the chemical composition of water and seabed sediment were detected, in particular, pH and dissolved inorganic carbon (DIC) of the sediment pore water during the CO_2 release. After the gas release was stopped, concentrations of all pore water constituents rapidly returned to pre-release values. The QICS team concluded that the environmental impacts from small-scale leakage is not ecologically significant.
We address two unsettled issues from QICS: (1) the mechanism behind the rapid recovery of pore water parameters to pre-release levels, and (2) the fate of the released CO_2 potentially remaining in the subsurface sediments. To settle these issues, we conducted field observation measurements at the QICS site, Ardmucknish Bay, in 2016, four years after the CO_2 release. Time series in situ monitoring of pore water chemistry in the subsurface sediments was conducted in order to investigate pore water dynamics. To characterize pore water behaviour more precisely, we conducted a tracer test using the custom-made pore water extractors. To trace the injected CO_2, carbonate content and stable carbon isotope ratio of the sediment and pore water were compared between the area close to the CO_2 release point and the unaffected reference site. In this presentation we focus on the pore water dynamics at the QICS site and show the results of field observation that influence benthic recovery from a CO_2 leak.

Keywords: CCS, global warming, sediment, pore water

Response of dimethyl sulfide production by phytoplankton to change in multiple environmental stressors in the western Arctic Ocean

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The Arctic Ocean environment is experiencing rapid climate changes such as warming, ocean acidification and sea ice reduction, influencing ecosystem dynamics including biogeochemical cycling. Dimethyl sulfide (DMS) and its major precursor dimethylsulfoniopropionate (DMSP) are produced through physiological function of phytoplankton in marine environment. It has been suggested that oceanic DMS emissions could play a dominant role in climate regulation on a regional basis especially in the polar region. Unraveling the response of marine organisms against such environmental perturbations is important to better understand the present and future Arctic Ocean ecosystem and production of DMS and DMSP. We investigated the effects of temperature, CO_2 and salinity on plankton communities, DMS and DMSP in the Arctic Ocean using on-board manipulation experiment during R/V *Mirai* MR15-03 cruise. Temperature (2.2 or 7.2°C), CO_2 (300 or 600 μatm) and salinity (29.4 or 27.8) were manipulated using thermostat circulator, the addition of high CO_2 seawater, and pure water, respectively. The higher temperature enhanced the growth of phytoplankton community in terms of chlorophyll-*a*. Nano-sized (~2–10 μm) phytoplankton growth was increased due to the higher temperature but not CO_2 in the community. On the other hand, pico-sized (< 2 μm) phytoplankton growth was unchanged during the incubation. DMS and DMSP concentration were getting higher during the experiment for all batches. We will further discuss the relationships between production of DMS and DMSP and changes in the biological variables in this presentation.

Keywords: dimethyl sulfide, DMS, DMSP, ocean acidification, Arctic Ocean