La mer 53 : 53–60, 2015
Société franco-japonaise d'océanographie, Tokyo

Temporal variation of microalgal chlorophyll *a* in surface ice and the underlying Water in lagoon Notoro-ko, Hokkaido, Japan.

Yasuto NISHINO[1), Tomoki SATOH[2) and Akira TANIGUCHI[3)

Abstract: Lagoon Notoro-ko is a large brackish lake on the Okhotsk Sea coast of Hokkaido. It is completely covered with sea ice during winter and hydrographic and biological conditions during this season are unknown. Previous investigations done in warm seasons indicate that the lagoon water is almost the same as the Okhotsk Sea water because there are few inflows from the land. We conducted a winter investigation into the temporal changes of microalgal chlorophyll *a* in the sea ice and water column beneath it during the period from February 6 to March 18, 2008. Of the surface PAR, 1% penetrated to 6–10 m depth in the water column beneath the ice, where 0.4–6.0 mg/m^3 chlorophyll *a* was detected. Integrated chlorophyll *a* in 18 m ranged 8.7–119.1 mg/m^2. In contrast, chlorophyll *a* levels in 20–31 cm thick ice ranged 2.5–11.6 mg/m^2, relatively less than in the water column. However, because chlorophyll *a* was largely concentrated in the bottom-most part of the ice, it might be available to grazers in the underlying water. During ice melting, a large proportion of the populations released from the ice likely sunk to the sea bottom rather than remaining in the water column.

Keywords : *ice algae, phytoplankton, chlorophyll a, Lagoon Notoro-ko*

1. Introduction

The Okhotsk Sea is a marginal subarctic sea in the western North Pacific. It is bordered by Siberia Russia in the north and west and by Hokkaido, Japan, in the south. It is the southern-most ice-covered sea in the northern hemisphere during winter (WATANABE, 1963; PARKINSON and GRATZ, 1983). Many of the lagoons and brackish lakes on the Okhotsk Sea coast of Hokkaido also freeze every winter. However, few studies on the relationship between sea ice and biological production have been conducted in the sea. One of the reasons for this is that the majority of the sea ice in the Okhotsk Sea is floe or drifting ice, which makes it very difficult to follow its effect on biological production over time. To avoid this difficulty, we focused on fast sea ice.

There are several lagoons and brackish lakes in the coastal region of eastern Hokkaido, Japan that are permanently connected to the Okhotsk Sea and freeze on the surface in winter. These lagoons and lakes are productive fishing grounds, particularly for marine demersal resources. Among them, Lagoon Notoro-ko is the second

1) Faculty of Bio-Industry Tokyo University of Agriculture, 196 Yasaka, Abashiri, Hokkaido 099–2493, Japan
2) Hokkaido National Fisheries Research Institute, Fisheries Research Agency, 2–2 Nakanoshima, Toyohira, Sapporo, Hokkaido 062–0922, Japan
3) Sanyo TechnoMarine, Inc., 1–3–17, Nihombashi-Horidomecho, Chuo-ku, Tokyo 103–0012, Japan

largest and its water is exchanged with the Okhotsk Sea water by tidal force. On the other hand, there is little inflow from land drainage. As a result, the physical and chemical properties of the lagoon water are quite similar to those of the Okhotsk Sea (IMADA *et al.*, 1995; NISHINO *et al.*, 2007). Because of this, the ice cover in Lagoon Notoro-ko can be considered as a fast ice of the Okhotsk Sea and a suitable stage to investigate the Okhotsk Sea ice (KURATA and NISHIHAMA, 1987; WATANABE *et al.*, 1991; ASAMI and IMADA, 2001).

The ice in Lagoon Notoro-ko starts to form in late December, becomes fast enough for human activities between late January and late March and melts away by mid-April. We conducted a series of investigations on the distribution of microalgal chlorophyll *a* in both the ice (ice algae) and the underlying water (phytoplankton) in February and March 2008. This paper reports temporal changes in the distributions of the ice algae and the phytoplankton and discusses the ecological role of the sea ice in the Okhotsk Sea.

2. Methods

Field surveys were conducted approximately once a week or five times in total during the period from February 6 to March 18, 2008, when on-ice activity was feasible, at a fixed station in the deepest part of the Lagoon Notoro-ko. Its geographical position is 44° 03′03″N, 144° 09′45″E, and the depth to the bottom is approximately 20 m (Fig. 1). Ice cores were taken with an ice auger of 7 cm in diameter and water samples were taken at 1 m, 5 m, 10 m, 15 m and 18 m with a Van Dorn bottle. Vertical temperature, salinity and density (sigma-t) profiles were recorded with a CTD (JFE Advantech, Model ASTD102). Penetration of photosynthetically active radiation (PAR) into the water column beneath the ice was measured with a quantum meter (JFE Advantech, AL30-CMP) by susupending the sensor into the underlying water column through the hole left after ice core sampling (diameter: ca. 10 cm). PAR at different depths is expressed in relative values (%) to that above the ice (in air).

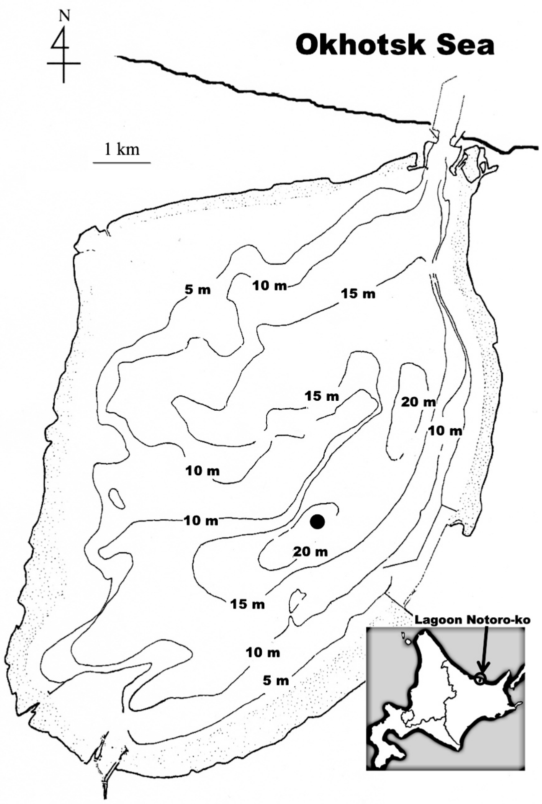

Fig. 1 Station (solid circle) for serial observations on microalgal chlorophyll *a* contents in ice cover and the underlying water column at the center of the deepest basin in Lagoon Notoro-ko onthe Okhotsk Sea coast of Hokkaido, Japan, from February 6 to March 18, 2008. Depth contours are given at 5 m intervals.

The ice cores were divided into five parts, i.e. upper, upper-middle, middle, middle-lower and lower. The upper, middle and lower parts were exactly 5 cm in length, while length of the upper-middle and middle-lower parts differed depending on the thickness of the ice on the day of survey. Each of the ice cores was thawed and chlorophyll *a* measured. Size-fractionated (> 10

Table 1. Underwater PAR (photosynthetically active radiation) at five sampling depths in values relative to those on the ice cover (%) during the ice-covered period from February 6 to March 18, 2008 in Lagoon Notoro-ko. Sea ice thickness (cm) is also given for each sampling day.

Sampling date (Ice thickness)	Feb. 6 (20)	Feb. 18 (29)	Feb. 29 (30)	Mar. 10 (31)	Mar. 18 (21)
Depth (m)	2.60	1.50	1.70	3.10	6.00
5	0.75	0.42	0.53	0.98	1.15
10	0.30	0.17	0.23	0.40	0.37
18	0.17	0.10	0.11	0.25	0.25
~20	0.11	0.07	0.03	0.24	0.11

μm, 2–10 μm, < 2 μm) chlorophyll *a* concentrations were measured in the seawater samples and thawed ice by a serial filtration through polycarbonate filters of 10 μm and 2 μm in pore size (Whatman) and a glass fiber filter (GF/F, Whatman). Chlorophyll *a* on the filters was extracted in dimethylformamide and measured with a fluorometer (Turner-Design, 10-AU) according to the Welschmeyer (1994).

3. Results and Discussion

3.1 Hydrographic conditions beneath ice cover (Fig. 2, Table 1)

Temperatures in the water column beneath the ice ranged from −2.3℃ to −1.0℃ and generally increased with depth. On February 18, supercool water below −1.8℃ had formed in the upper 5 m and, as a result, an inverse thermocline formed around 5 m. Thereafter, temperature gradually increased at every depth, particularly below 10 m, and a thermocline formed around 15 m.

Salinity was < 32.7 throughout the water column during the survey period, except for February 18, when very saline water appeared in the surface and bottom layers (maximum: 33.3). On February 29, it was indicated that the saline surface water has sunk and been diluted. Salinity dropped to < 32.4 through the water column in March. Very low salinity water was detected at the surface (minimum: 29.3) on March 18.

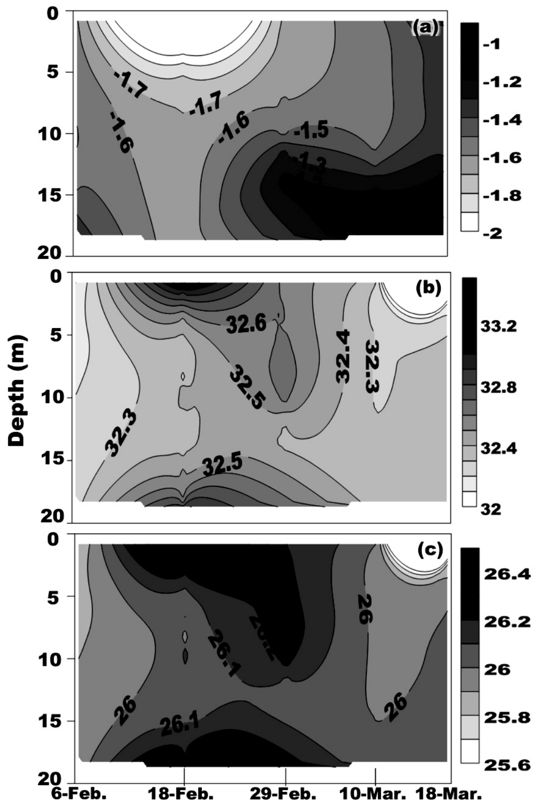

Fig. 2 Time courses in vertical section of temperature (a: ℃), salinity (b) and density (c: sigma-T) in the water column observed during the ice-covered period from February 6 to March 18, 2008, at the fixed station in Lagoon Notoro-ko on the Okhotsk Sea coast of Hokkaido, Japan. The bottom depth was about 20 m.

Sigma-t was over 26 in most cases, which was higher than that in warm seasons, i.e. 21.5–26.1 (NISHINO unpublished data). The temporal and vertical changes of sigma-t generally followed those of salinity. High sigma-t values, > 26.9, were observed in both the surface and bottom layers on February 18. The lowest density (23.5) was observed on March 18 in the diluted surface water.

A coastal divergence from the East Sakhalin Current reaches the coast of eastern Hokkaido in autumn and winter (OHSHIMA *et al*., 2002; SHIMIZU and OHSHIMA, 2006), which is characterized by salinities below 32 (FUJII and SATOH, 1979; TAKIZAWA, 1982). Salinity at or below 32.4 in the coastal water in winter indicates the presence of the East Sakhalin Current (AOTA, 1979). The present results revealed the intrusion of this water mass (< 32.4) into Lagoon Notoro-ko in winter. Within this water mass, high salinity water appeared separately in the surface and the bottom layers in late February, forming an inverse pycnocline in the surface and a normal pycnocline in the bottom layer. Such unusual stratification indicates that some unfrozen brine water had sunk rapidly to the bottom before February 18 and the exclusion of the brine continued until February 29. We conclude that ice is most actively formed in February in Lagoon Notoro-ko. In March, the low salinity water affected by the East Sakhalin Current again filled the entire water column, except for the surface water which was diluted by melting ice. It is possible that the high salinity bottom water observed in February may have been the result of a temporary intrusion of Okhotsk Sea Intermediate Cold Water, which is highly saline being 32.8–33.3 (TAKIZAWA, 1982). If it had been the case, it occurred within a very short period and was limited to a thin bottom layer (Fig. 2). Therefore, it is a reasonable conclusion that the water mass occupying Lagoon Notoro-ko during winter is basically the coastal water affected by the East Sakhalin Current and temporarily modified by the formation and melting of the ice. Further investigations on nutrient compositions and plankton assemblages are necessary.

Table 1 shows underwater PAR intensities in relative values (%) to that above the ice. Relative PAR at 5 m depth was 2.6% on February 6; it decreased afterwards in February (1.5–1.7%) and increased again to 6.0% in March. PARs at other depths varied in parallel with this. The 1% PAR depth, which is generally assumed to be the compensation depth of phytoplankton photosynthetic production, was 6.5–10.7 m during the entire period, indicating that positive production was continually performed at significant depths through the ice covered period. This is not surprising because the lagoon is located in the southern half of the northern hemisphere (44° 03' N). Recorded values of the ten-day average of daily solar irradiance during the same period were 5.3–7.1 MJ/m^2 in January, 8.8–10.5 MJ/m^2 in February and 11.9–12.5 MJ/m^2 in March, which were about 23–54% of the annual maximum recorded in middle of May (23.1 MJ/m^2) of the same year (JAPAN METEOROLOGICAL AGENCY, 2008).

KISHINO (1993) reported that relative PAR beneath 33 cm thick ice was about 0.7% under natural conditions and about 4% after the removal of snow that had accumulated on the ice in Lagoon Saroma-ko, about 100 km north of Lagoon Notoro-ko. Although this demonstrates that light penetration through ice is largely obstructed by snow accumulation, such heavy accumulation was not recorded on any occasion in the present investigation in Lagoon Notoro-ko. The reason for this difference between lagoons is not clear at present.

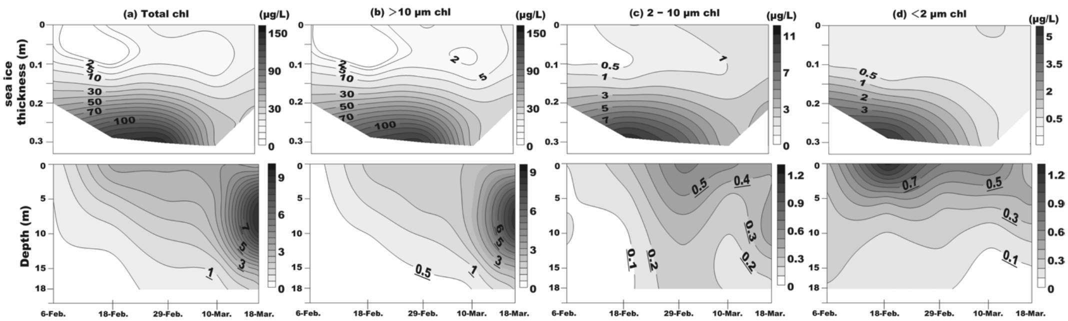

Fig. 3 Vertical section of total chlorophyll *a* over time (a), large-sized chlorophyll *a* > 10 μm (b), medium-sized chlorophyll *a* 2–10 μm (c) and small-sized chlorophyll *a* < 2 μm (d) in 20–31 cm thick sea ice (upper) and the underlying water column down to 18 m (lower) from February 6 to March 18, 2008. The bottom depth was about 20 m.

3.2 Chlorophyll a (Fig. 3)

Chlorophyll *a* concentration in the ice was 2.2–8.4 μg/L in the upper part, 2.8–13.4 μg/L in the middle part and 21.8–163.6 μg/L in the lower part. This demonstrates that so-called ice algae (microalgal communities within sea ice) can attain very high densities particularly in the lower part of the ice. Fig. 3 shows that their density gradually increased during the course of ice development until the end of February, but suddenly decreased when the ice started melting in early March. Among the ice algae, the large size class (> 10 μm) always predominated, while intermediate (2–10 μm) and small (< 2 μm) size classes usually contributed less than 20%. The exclusive dominance of the large size class was constant throughout the survey period. Similar trends of vertical and temporal variations of the ice algal chlorophyll *a* had been observed in a preliminary survey done in the preceding winter; while absolute concentration was apparently different between deep central area (this station) and shallow near-shore area, the trends were essentially the same in different areas. Similarity in concentration between several ice cores collected from the area of ca. 1 m^3 had also been confirmed.

The sudden decrease in chlorophyll *a* in the ice from February 29 to March 10 is remarkable and interesting. Because the ice was approximately the same thickness in this period, it is unlikely that the lower layer of the ice holding dense algae had melted. It must be noted that chlorophyll *a* in the middle part also dropped markedly from 13.4 to 3.3 μg/L in the same period. One possible explanation for this decrease is as follows: As solar radiation and air temperature increased (data not shown), the ice might start melting internally before the surface temperature of the underlying water increased to the melting temperature of the sea ice (−1.8℃). The internal melt probably progressed around brine pockets, which are characteristic of sea ice. The pockets gradually expanded and the ice algae inside were released into the underlying water. During this, the thickness of the ice might have remained unchanged.

Released ice algae partly contributed to an increase in phytoplankton in the underlying water column. As seen in Fig. 3, such a contribution to phytoplankton increase was positive in the smaller size classes but less so in the large size class. The latter indicates that the large-sized ice algae, probably in the form of colonies or aggregates,

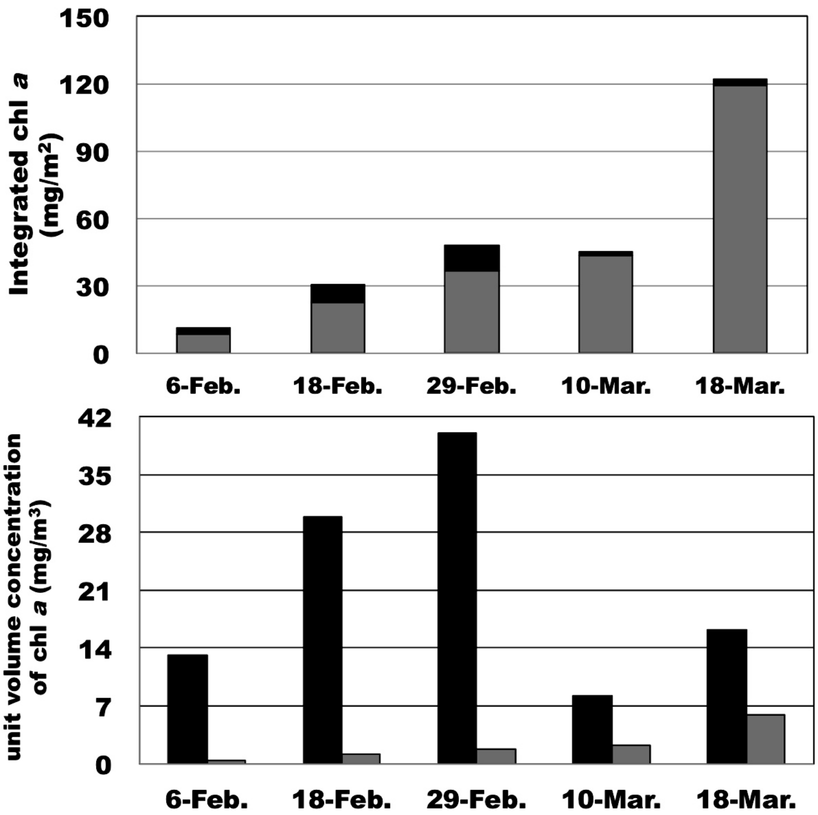

Fig. 4 Temporal changes in chlorophyll *a* stocks in the ice cover (■) and the underlying water column (■) in total amount (upper: mg/m^2) and average concentration (lower: mg/m^3) observed during the ice-covered period from February 6 to March 18, 2008, in Lagoon Notoro-ko, Hokkaido, Japan.

sunk down to the sea bottom rapidly and were hardly sampled with a Van Dorn bottle. If so, a large proportion of the ice algae contributed to the benthic rather than planktonic community. A bloom of the larger phytoplankton occurred on March 18, well after the major decrease of large-sized ice algae and took place in subsurface layer (5–10 m) instead of the surface layer underneath the melting ice (Fig. 3b). Since PAR at 10 m on March 18 was 1.15% (Table 1), blooming in the 5–10 m layer was natural. It is interesting to note that the larger phytoplankton avoided the low salinity surface water underneath the melting ice but the smaller size classes did not. This demonstrates that ice algae and phytoplankton populations interact differently in different size classes.

3.3 Integrated chlorophyll *a* in ice and water column (Fig. 4)

The amount of integrated chlorophyll *a* through the ice cores was 2.5 mg/m^2 at beginning, increased steadily to a maximum of 11.6 mg/m^2 on February 29 and dropped to 1.7 and 2.7 mg/m^2 on March 10 and 18, respectively. During this period, since ice thickness was more or less constant at 20–31 cm (Fig. 3), accumulation and loss of chlorophyll *a* should have occurred in the bottom part of the ice. The sudden decrease in chlorophyll *a* on March 10, when the thickness of the ice was still increasing, albeit marginally, is interesting (Fig. 3). This implies that release of the ice algae into the underlying water column is triggered by the widening of the brine pockets inside the ice, not because of the collapse of the sea ice, as discussed in the preceding chapter.

Integrated chlorophyll *a* through water column to 20 m depth differed from that in the ice over time. Chlorophyll *a* continually increased in the water column from 8.7 mg/m^2 on February 6 to 43.7 mg/m^2 on March 10 and finally reaching 119.1 mg/m^2 on March 18. Consequently, the ratio of the ice algae to phytoplankton in total chlorophyll *a* was relatively high before March 10 with a maximum of about 25% on February 29, but decreased sharply to about 2% in March. Nevertheless, the average chlorophyll *a* concentration in the ice was always higher than in the water column even on March 18 when the phytoplankton bloom occurred. Because it is generally known that the density of dietary microalgae positively affects herbivore feeding efficiency, the sea ice provides herbivores with efficient grazing areas, especially on its under surface exposed to the water. Benthopelagic mysids and shrimps were occasionally observed with abundant copepods in the surface layer at the present investigation site (data not shown).

4. Conclusions

The present study site, Lagoon Notoro-ko, is located in the southern half of the northern hemisphere. This makes the light conditions in the water column under ice cover essentially different to that in high arctic seas. In the high arctic, because solar radiation in winter is generally low and largely reflected by snow and ice, underwater light conditions are very poor and thus phytoplankton production is negligibly low. In contrast, except on the occasional heavy snow days, phytoplankton photosynthetic production in Lagoon Notoro-ko is not limited in this way. The present results evidently show that, in the water column covered with 20–31 cm ice, the 1% PAR depth (compensation depth) was as deep as 6.5–10.7 m (cf. Table 1). The phytoplankton chlorophyll *a* concentration was well over 1.0 μg/L to the depths throughout winter (Fig. 3). This level of chlorophyll *a* is comparable to those in warm seasons (Kurata and Nishihama, 1987; Nishino *et al.*, 2014). The brackish nature of the lagoon water might benefit this; the water column is easily stratified and holds phytoplankton in the shallower layers.

Stocks of chlorophyll *a* within the ice (ice algae) were also notably large. Integrated chlorophyll *a* was comparatively smaller than in the underlying water column but its concentration was very high (Fig. 4). A certain proportion of the ice algal populations is continuously released into the water. This might form an efficient forage site of filter feeders in the underlying water, because they prefer dense food suspension to phytoplankton distributed over wide water column (Parsons and Takahashi, 1973; Taniguch, 1975). Since major part of the ice algae is concentrated into the bottom-most part of the ice, their products are partly available to grazers including benthopelagic organisms on the under-surface of the ice. We also suggest that most of the large-sized ice algae sink directly to the sea bottom in late February (Fig. 3), which might be consumed by benthic grazers. Such contribution of the ice algae could be determined by collecting the sinking colonies with e.g. sediment traps in future survey.

In summary, sea ice is a unique ecological platform, where microalgae perform three primary producer roles, i.e. produce nutrient rich products (pasture), allow grazers to feed on the products (meadow) and transport products to the benthic community (feeder).

References

AOTA, M. (1979): Oceanographic conditions in the coastal area of southwestern Okhotsk Sea. Bull. Coast. Oceanogr., **17**, 1–11.

ASAMI, H. and K. IMADA (2001): Ice algae and phytoplankton in the late ice-covered season in Notoro Ko lagoon, Hokkaido. Polar Biosci., **14**, 24–32.

FUJII, K. and Y. SATOH (1979): Oceanographic structure and production in Japan Sea and costal Okhotsk Sea. Bull. Jpn. Soc. Fish. Oceanogr., **34**, 57–62.

IMADA, K., S. SAKAZAKI, T. KAWAJIRI and K. KOBAYASHI (1995): Lake basin and saline environments profiles of four brackish lakes in Abashiri, northern Hokkaido. Sci. Rep. Hokkaido Fish. Hatchery, **49,** 37–48.

JAPAN METEOROLOGICAL AGENCY (2008): Global solar radiation and temperature in Abashiri in 2008, at http://www.data.jma.go.jp/obd/stats/etrn/, accessed 13 October 2015.

KISHINO, M. (1993): Spectral light environment in/under sea ice in Lake Saroma. Bull. Plankton Soc. Japan., **39**, 161–165.

KURATA, M. and Y. NISHIHAMA (1987): Seasonal change of the hydrographic condition in Lake Notoro, Hokkaido. J. Hokkaido Fish. Exp. Sta., **29,** 17–24.

NISHINO, Y., T. SATOH, K. ASAKUMA, A. SHIOMOTO and A. TANIGUCHI (2007): Seasonal and Vertical Distribution of Phytoplankton and Nutrients in Lagoon Notoroko on the coastal Okhotsk Sea. Proc. Application of a Closed Experimental System to Modeling of 14C Transfer in the Environment, 196–201.

NISHINO, Y., T. SATOH, A. SHIOMOTO and A. TANIGUCHI (2014): Lower trophic levels of coastal marine ecosystem in Lagoon Notoroko on the coastal Okhotsk Sea --seasonal change of size fractionated chlorophyll a and dissolved inorganic nitrogen--. J. Agric. Sci., Tokyo Univ. Agric. **59** (1), 11–20.

OHSHIMA, K. I., M. WAKATSUCHI and Y. FUKAMACHI (2002): Nearsurface circulation and tidal currents of the Okhotsk Sea observed with satellite-tracked drifters. J. Geophys. Res., **107** (C11), 3195.

PARKINSON, C. L. and A. J. GRATZ (1983): On the seasonal sea ice cover of the Sea of Okhotsk. J. Geophys. Res., **88**, 2793–2802.

PARSONS, T. R. and M. TAKAHASHI (1973): Biological Oceanographycal Processes, Pergamon Press, Oxford, New York, 186pp.

SHIMIZU, D. and K. I. OHSHIMA (2006): A model simulation on the circulation in the Sea of Okhotsk and the East Sakhalin Current. J. Geophys. Res., **107** (C11), 3195.

TAKIZAWA, T. (1982): Characteristics of the Soya Warm Current in the Okhotsk Sea. J. Oceanogr. Soc. Japan, **38**, 281–292.

TANIGUCHI, A. (1975): Production Ecology of Zooplankton. *In* Marine plankton. MOTODA, S. (ed.), Tokai University Press. p. 117–235.

WATANABE, K. (1963): On the reinforcement of the East Sakhalin Current preceding to the sea ice season off the coast of Hokkaido—Study on the sea ice in the Okhotsk Sea (IV). Oceanogr. Mag., **14**, 117–130.

WATANABE, K., H. SATOH, Y. YAMAGUCHI, A. TANIMURA, T. KONO, Y. INOUE and M. FUKUCHI (1991): Ice algal assemblages from lagoons Saroma-Ko, Notoro Ko and Akkeshi-Ko in Hokkaido. Abstracts of The Sixth International Symposium. The Okhotsk Sea and Sea Ice. Monbetsu, 75–79.

WELSCHMEYER, M.A. (1994): Fluorometric analysis of chlorophyll *a* in the presence of chlorophyll *b* and pheopigments. Limnol. Oceanogr., **39** (8), 1985–1992.

Received: September 7, 2015
Accepted: November 7, 2015