JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. C3, PAGES 4673–4680, MARCH 15, 1995

# An in situ experimental study of young sea ice formation on an Antarctic lead

Igor Melnikov

P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow

**Abstract.** Three series of experimental results were obtained in situ during the U.S.-Russian Ice Station Weddell 1 Expedition 1992 in the western Weddell Sea. Changes in salinity, silicate, and chlorophyll *a* concentrations were examined over sampling scales of hours, days, and months as microalgal populations grew in young sea ice. Sea ice growth rates were 0.38 cm $h^{-1}$ for ice up to 9 cm (May 19–20), 0.13 cm $h^{-1}$ for ice growth to 28 cm over the next 8 days, and 0.03 cm $h^{-1}$ during 81 days of observations on ice 42–97 cm thick (March 18–June 7). It was shown that at the initial stage of ice formation, salt and nutrient accumulation occurred, then ice desalination intensified with increasing ice thickness. Brine within the ice showed a 12-hour period of oscillatory motion during the first day of ice growth and a 1.5- to 2-hour oscillation in the skeletal layer of 28-cm ice. Small numbers of diatoms were entrapped from seawater during the initial ice formation. Their reproduction (in terms of chlorophyll *a* concentration) markedly increased after the third day of ice formation. The highest concentrations of chlorophyll *a* (100 to 1000 times higher than the underlying seawater) were recorded within the bottom, brown-colored layer of all young ice cores studied during the 81-day experiment. The species composition of ice algal populations (99 species) was more diverse and rich than observed for phytoplankton (18 species) in surface seawater. The temporal and spatial distribution of all parameters studied were controlled by meteorological factors and brine drainage mechanisms.

## 1. Introduction

Sea ice is an important component of the Southern Ocean ecosystem. In general, the extent of the ice cover increases from a minimum of $4 \times 10^6$ $km^2$ in February to a maximum of $20 \times 10^6$ $km^2$ in September [*NASA*, 1987]. Within the Antarctic sea ice zone, mean ice concentrations range from about 50% in summer to 80% in winter [*NASA*, 1987], indicating the existence of leads or polynyas during the annual growth and decay of Antarctic sea ice.

Leads and polynyas are important contributors to physical oceanic processes, such as ocean/atmosphere energy exchange [*Smith et al.*, 1990]. Their contribution to biological processes, such as microbial colonization, during initial ice formation and implications from subsequent development/succession of microbial communities remain unclear. To better understand the ecological role of leads and polynyas and thus the ecological function of the Antarctic sea ice zone, questions regarding spatial and temporal patterns of microbial colonization and growth in sea ice during initial ice formation and ice growth and the structure of these sea ice microbial communities must be addressed.

Our knowledge of the Antarctic sea ice biology is based mainly on the observations in the coastal regions [*Meguro*, 1962; *Bunt and Wood*, 1963; *Burkholder and Mandelli*, 1965; *Hoshiai*, 1977; *Sullivan and Palmisano*, 1981] where benthic communities greatly influenced the structure and dynamic of the sea ice ecosystem. Several studies have examined microbial colonization, growth, and community structure in pelagic Antarctic sea ice [*Garrison and Buck*, 1982; *Ackley et al.*, 1987; *Bartsch*, 1989]. During the Weddell Polynya Expedition in October–November 1981, *Clarke and Ackley* [1984] found that frazil ice formation in winter concentrated algal cells from the water column onto ice floes, resulting in higher chlorophyll *a* concentrations in sea ice relative to the adjacent water. This difference was further enhanced during the subsequent growth of ice algae. Chlorophyll *a* concentrations within drifting sea ice ranged from 0.1 to 3.8 mg $m^{-3}$ in the eastern Weddell Sea and were significantly lower than measurements from fast ice in coastal regions (300–2000 mg $m^{-3}$) [*Sullivan and Palmisano*, 1981]. Ice structure was one of the major factors influencing the abundance of biological communities in polynya and coastal areas [*Clarke and Ackley*, 1984].

A multidisciplinary study of the sea ice during the joint U.S.-Russian Expedition on Ice Station Weddell 1 (ISW 1) [*Gordon and Lukin*, 1992] provided an excellent opportunity to examine ice dynamics, the microbiological community, and the nature and rates of biotic processes during initial ice formation and colonization of lead ice. This paper presents hourly, daily, and monthly observations of physical, chemical, and biological processes during the formation and growth of young sea ice in austral autumn. These observations were taken in a region of perennial ice in the western Weddell Sea during the drift of ISW 1 from 72 to 65°S and 51 to 53°W (Figure 1).

## 2. Methods

Field observations were conducted in newly formed leads at the edge of the floe on which the ice camp was located. Sampling strategy was based on the following: (1) observa-



Paper number 94JC02354.
0148-0227/95/94JC-02354$05.00

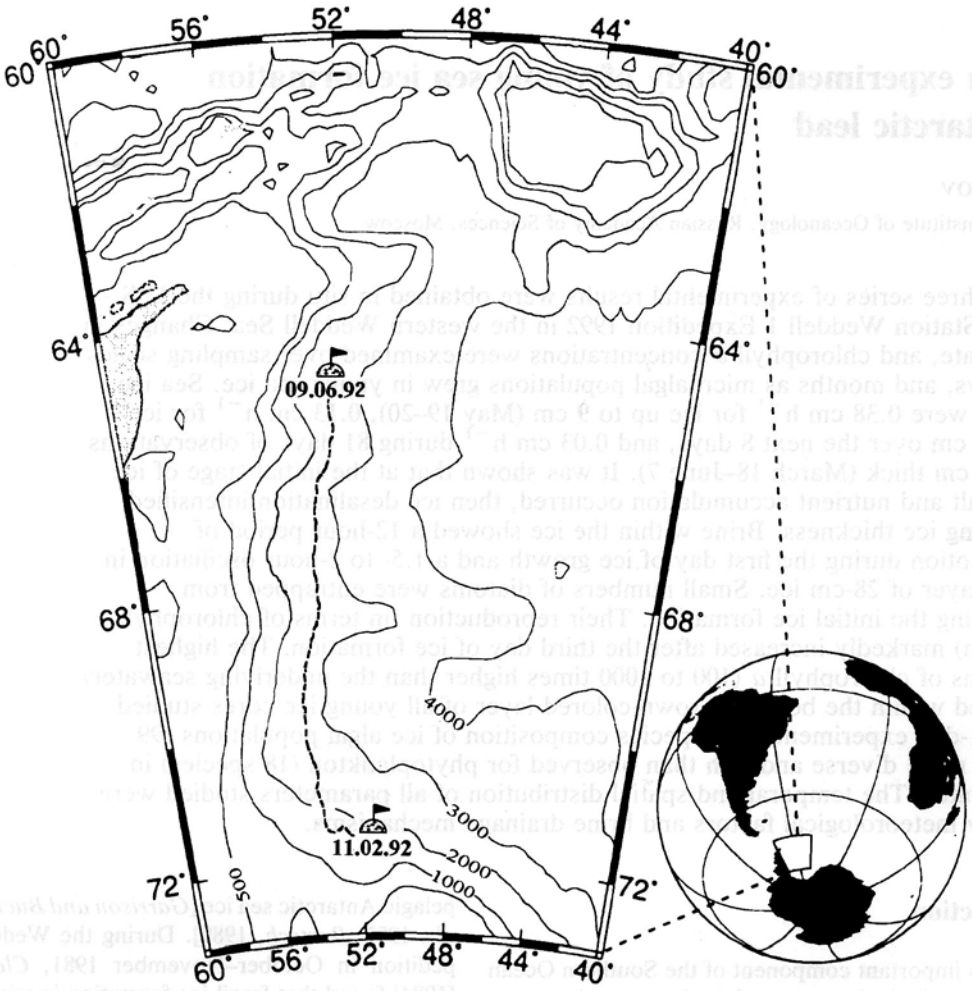


**Figure 1.** Track of the U.S.-Russian Ice Station Weddell-1 (ISW-1) Expedition (February 11 to June 9, 1992).

tions on a lead with newly formed sea ice (May 20–28, experiment 1), (2) hourly small-scale observations on a lead with young sea ice (May 25, experiment 2), and (3) monthly observations of young growing sea ice (March 18–June 7, experiment 3).

During these three experiments, which were conducted in late austral autumn and early austral winter, incident solar radiation and air temperatures decreased, while snow accumulation increased. Figure 2 shows daily infrared sea ice surface temperature variations during the period of experiments.

Ice samples were taken with a 10-cm diameter ice-coring auger. Each ice core was divided into 10- or 20-cm long sections, and these subsamples were used for analyses of salinity, silicate, chlorophyll *a*, and species composition. Subsamples were melted at room temperature and immediately analyzed for salinity and silicate. Meltwater salinity was obtained with a Beckman salinometer; silicate was determined using the method of *Strickland and Parsons* [1968]. Chlorophyll *a* samples were filtered through GF/A glass fiber filters (nominal pore size 1.6 $\mu$m) and frozen until analysis several days later using the method and equations for the calculation of chlorophyll *a* concentrations from *Scientific Committee on Oceanic Research-UNESCO* [1966].

Brine sampling was carried out during ice coring from the holes using 20- and 50-mL volume plastic syringes with 25-mm long plastic needles. Brine was collected in plastic centrifuge tubes. In the laboratory, brine samples were diluted with distilled water, so that salinities were similar to seawater, then salinity and silicate were measured identically to ice samples as discussed above.

Similar information for the underlying seawater in contact with the underside of the sea ice was obtained from samples collected using a 2-L plastic syringe while Scuba diving. Samples to determine phytoplankton composition were collected every 10 days by pumping 50 L of the surface seawater from an ice hole to a plastic tank. Phytoplankton were concentrated to 50 mL using a reverse filtering system with a 10-$\mu$m mesh nylon filter. Samples were fixed with 4% formaldehyde. Species identification and enumeration, both of phytoplankton and sea ice algae, were conducted using standard procedures in planktonology [*Kisilev*, 1969].

## 3. Results

### 3.1. Experiment 1

This experiment, summarized in Table 1, was carried out on a lead which formed on May 17. After 17 cm of new ice had formed over the lead, 14 test holes (1 $m^2$) were created.

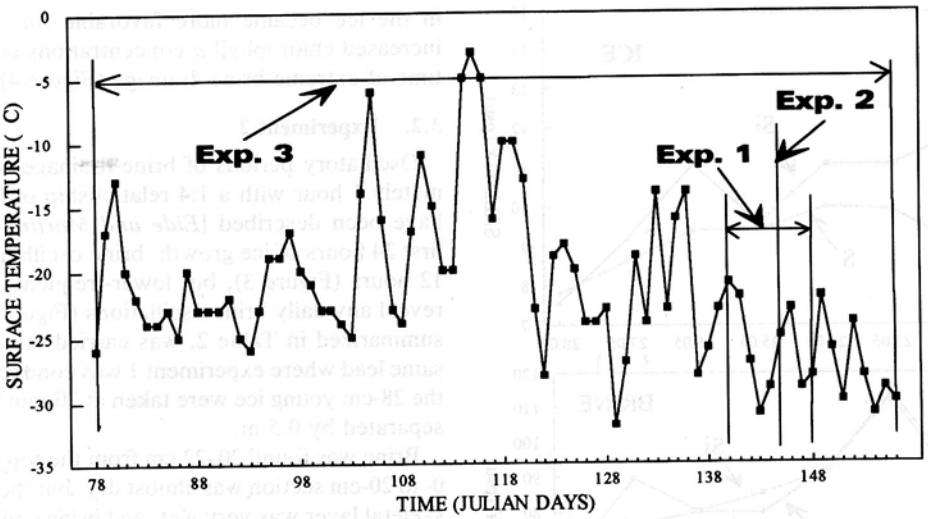


**Figure 2.** Daily infrared sea ice surface temperature (in degrees Celsius) during the period of experiments (ISW 1, March–June 1992) as follows: experiment 1 (May 20–28), experiment 2 (May 25), and experiment 3 (March 18–June 7).

These test holes were cleared of all ice at 2000 UT May 19, and the first observation was made at 0000 UT on May 20. Ice cores and brine were sampled from different test holes every 4 hours on May 21 (cores A6C1–A6C7). After 24 hours, ice cores and brine were collected from different test holes once per day until May 28 (cores A6C8–A6C15).

Ice growth rates were 0.38 cm $h^{-1}$ during the first 24 hours of ice growth and 0.13 cm $h^{-1}$ during the next 8 days. The incorporation of salts (in terms of salinity and silicate) and particulate matter (chlorophyll *a*) was nonlinear for the first 24 hours (or 9 cm) of ice formation (Figure 3). During the first 8 hours the maximum ice growth rate was observed and the salinity and silicate concentrations in ice increased to 19 practical salinity units (psu) and 950 $\mu$g $L^{-1}$, respectively, then rapidly decreased. Values continued to decrease during

**Table 1.** Summary of Experiment 1

| Sample | Date of Sampling | Time of Sampling, UT | Ice Thickness, cm | Latitude, °S | Longitude, °W |
|---|---|---|---|---|---|
| A6C1 | 20.05 | 24 | 1.86 | 67.4 | 53.3 |
| A6C2 | 20.05 | 04 | 2.53 | ... | ... |
| A6C3 | 20.05 | 08 | 4.77 | ... | ... |
| A6C4 | 20.05 | 12 | 6.33 | ... | ... |
| A6C5 | 20.05 | 16 | 5.80 | ... | ... |
| A6C6 | 20.05 | 20 | 7.37 | ... | ... |
| A6C7 | 20.05 | 24 | 9.13 | 67.4 | 53.3 |
| A6C8 | 21.05 | 12 | 11.6 | 67.3 | 53.3 |
| A6C9 | 22.05 | 12 | 17.3 | 67.2 | 53.3 |
| A6C10 | 23.05 | 12 | 23.0 | 67.0 | 53.3 |
| A6C11 | 24.05 | 12 | 25.5 | 66.8 | 53.2 |
| A6C12 | 25.05 | 12 | 26.5 | 66.5 | 53.1 |
| A6C13 | 26.06 | 12 | 29.0 | 66.3 | 53.0 |
| A6C14 | 27.05 | 12 | 28.0 | 66.2 | 52.9 |
| A6C15 | 28.05 | 12 | 34.0 | 66.0 | 52.8 |

Conditions during this Experiment 1 were as follows: air temperature ranged from −22 to −31°C; water salinity and temperature were 34.4 psu and −1.86°C, silicate and chlorophyll *a* concentrations were 1560 $\mu$g/L and 0.24 $\mu$g/L, respectively; phytoplankton was dominated by *Thalassiosira antarctica* (28.6%), *Fragilariopsis cylindrus* (28.6%), *Pinnularia quadratarea* (14.2%), *Thalassionema nitzschioides* (14.2%), and *Aulacosira sp.* (0.1%).

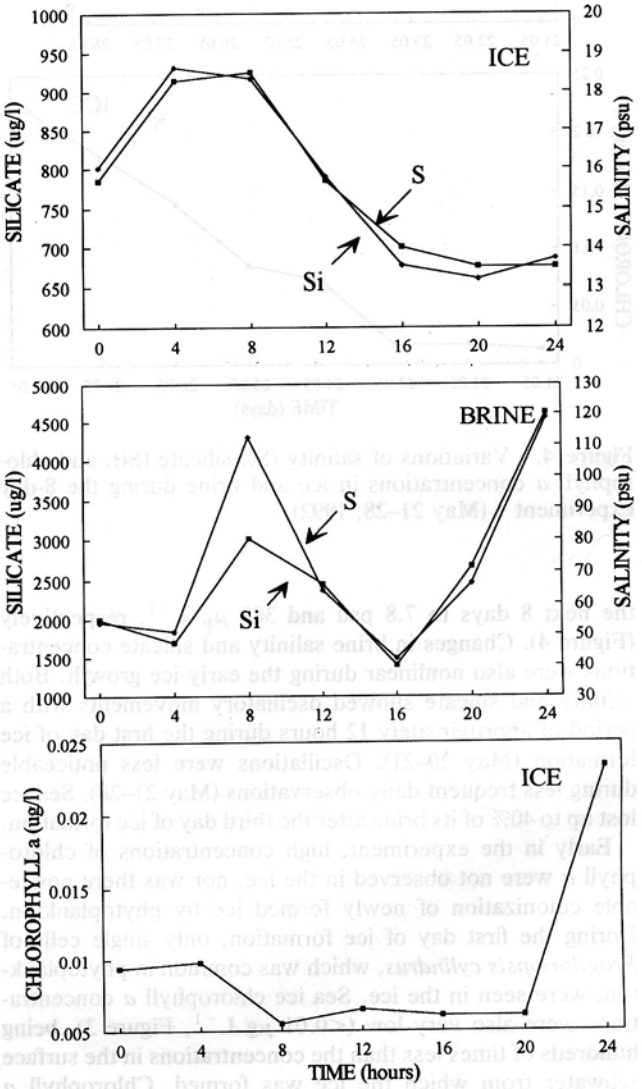


**Figure 3.** Variations of salinity (S), silicate (Si), and chlorophyll *a* in ice and brine in the newly formed young ice during the 24-hour experiment 1 (May 20–21, 1992).

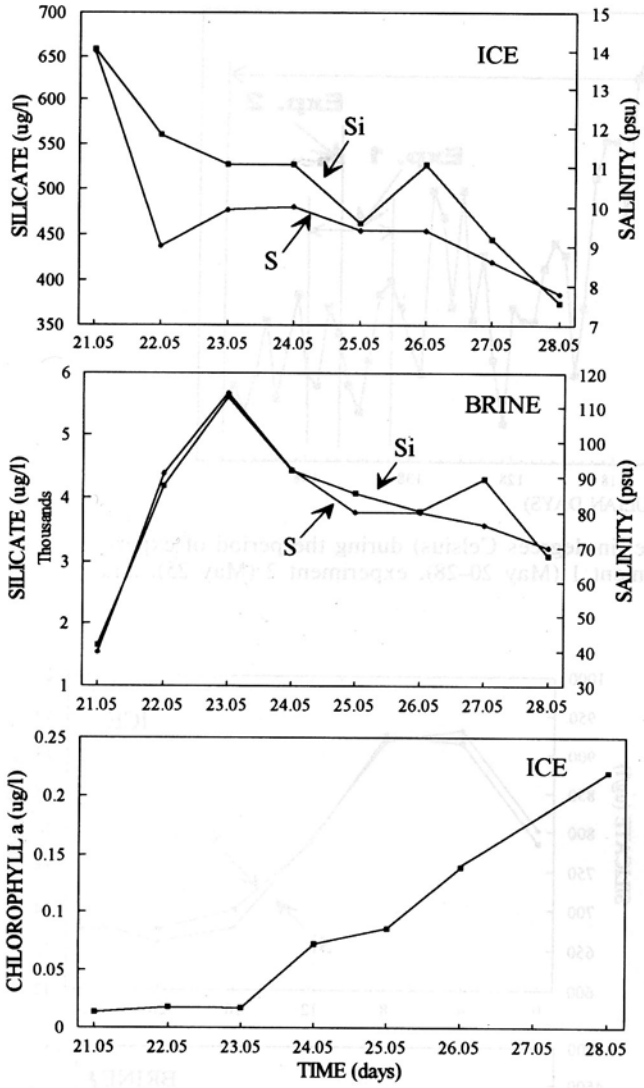


**Figure 4.** Variations of salinity (S), silicate (Si), and chlorophyll *a* concentrations in ice and brine during the 8-day experiment 1 (May 21–28, 1992).

the next 8 days to 7.8 psu and 380 $\mu$g $L^{-1}$, respectively (Figure 4). Changes in brine salinity and silicate concentrations were also nonlinear during the early ice growth. Both salinity and silicate showed oscillatory movements with a period of approximately 12 hours during the first day of ice formation (May 20–21). Oscillations were less noticeable during less frequent daily observations (May 21–28). Sea ice lost up to 40% of its brine after the third day of ice formation.

Early in the experiment, high concentrations of chlorophyll *a* were not observed in the ice, nor was there noticeable colonization of newly formed ice by phytoplankton. During the first day of ice formation, only single cells of *Fragilariopsis cylindrus*, which was common in phytoplankton, were seen in the ice. Sea ice chlorophyll *a* concentrations were also very low (<0.01 $\mu$g $L^{-1}$, Figure 3), being hundreds of times less than the concentrations in the surface seawater from which the ice was formed. Chlorophyll *a* content increased on day 3 of the experiment, and on day 8 the concentration was the same order of magnitude as that in the seawater. Probably by day 3, environmental conditions in the ice became more favorable for algae growth. The increased chlorophyll *a* concentrations corresponded to the time of extreme brine drainage (Figure 4).

### 3.2. Experiment 2

Oscillatory periods of brine drainage in vitro of approximately 1 hour with a 1:4 relationship of inflow and outflow have been described [*Eide and Martin*, 1975]. During the first 24 hours of ice growth, brine oscillation had a period of 12 hours (Figure 3), but lower-frequency sampling did not reveal any daily brine oscillations (Figure 4). Experiment 2, summarized in Table 2, was carried out on May 25 on the same lead where experiment 1 was conducted. Samples from the 28-cm young ice were taken at 30-min intervals and were separated by 0.5 m.

Brine was found 20–22 cm from the top of the ice. The top 0- to 20-cm section was almost dry, but the bottom 6- to 8-cm skeletal layer was very wet, and brine collected from the top of this layer. The dynamic of brine salinity and silicate concentrations for 11 ice cores sampled during 5.5 hours are shown in Figure 5. This shows a 1.5- to 2-hour oscillatory period with a 1- to 1.5-hour inflow and a 0.5-hour outflow of brine within the 6- to 8-cm thick skeletal layer. Average values of minimum–maximum brine salinity were 64 and 83.2 psu, and silicate concentrations were 3525 and 4353 $\mu$g $L^{-1}$, respectively. This means that 23% of brine in terms of salinity and 19% in terms of silicate are renewed every 1.5–2 hours, an inflow and outflow period about twice as long as that described by *Eide and Martin* [1975].

### 3.3. Experiment 3

Observations, summarized in Table 3, were carried out at a second lead site which was covered with young sea ice. Ice cores from this lead (A3C1–A3C10) were taken every 7–10 days between March 18 (70.40°S, 53.40°W) and June 7 (65.80°S, 52.70°W). Ice thickness increased from 42 cm in March to 97 cm in June at a growth rate of 0.03 cm $h^{-1}$.

Structurally, the growing young ice was similar to a scheme described by *Weeks and Ackley* [1982] with a 10- to 20-cm snow layer, a transition zone with irregular crystal orientation, a layer of congelation ice, and a skeletal layer with vertical crystal orientation. The thickness of an algal brown layer varied from sample to sample but was always located near the bottom of the ice core.

Salinity, silicate, and chlorophyll *a* concentrations are

**Table 2.** Summary of Experiment 2

| Samples | Time of Sampling, UT | Ice Thickness, cm |
|---|---|---|
| A7C1 | 9.30 | 27.0 |
| A7C2 | 10.00 | 27.0 |
| A7C3 | 10.30 | 27.0 |
| A7C4 | 11.00 | 28.0 |
| A7C5 | 11.30 | 27.5 |
| A7C6 | 12.00 | 28.0 |
| A7C7 | 12.30 | 28.0 |
| A7C8 | 13.00 | 28.0 |
| A7C9 | 13.30 | 28.5 |
| A7C10 | 14.00 | 28.7 |
| A7C11 | 14.30 | 28.8 |

Air temperature during Experiment 2 was −23°C; surface seawater temperature, salinity, silicate, and chlorophyll *a* concentrations were −1.83°C, 34.42 psu, 2000 $\mu$g/L, and 0.024 $\mu$g/L, respectively.

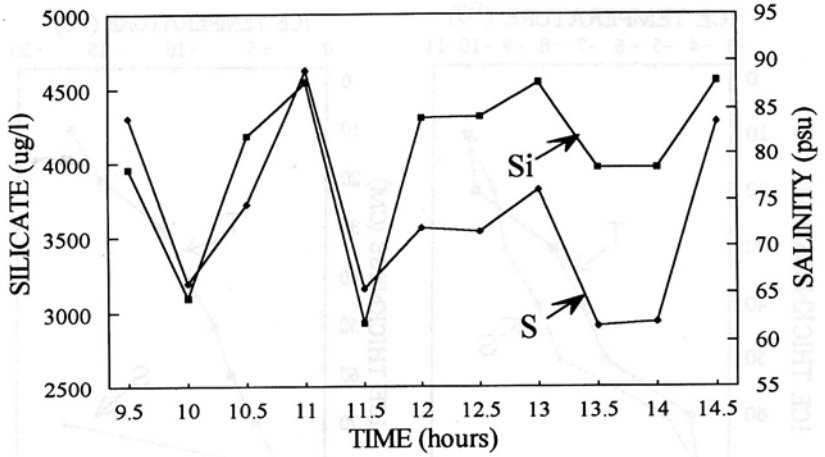


**Figure 5.** Variations of brine salinity (S) and brine silicate (Si) within the skeletal layer of 28-cm thick young sea ice during the 5.5-h experiment 2 (May 25, 1992).

plotted in Figure 6 for Julian days 78–159. Upper, middle, and lower layers are shown for each ice core, and with the exception of chlorophyll *a* these layers were relatively similar. Temperatures in the lower layer were closer to seawater temperatures, a thermal environment which may have promoted more vigorous algal growth in the lower layer relative to the upper and middle layers. Salinity, silicate, and chlorophyll *a* were highest from 85–110 Julian days (7–8 psu, 500–680 $\mu g\ L^{-1}$, and 25–33 $\mu g\ L^{-1}$, respectively) and lowest from 117–125 Julian days (3–4 psu, 20–100 $\mu g\ L^{-1}$, and 5–6 $\mu g\ L^{-1}$, respectively). During the course of these observations, temperatures at the ice surface increased from −25° to −2°, then rapidly decreased to −33°C (Figure 2). In general, the highest values were observed earlier in the experiment when temperatures were cold but increasing, and solar irradiance was relatively high.

The distribution of ice temperature and brine salinity ice cores A3C8 and A3C9, which were sampled on Julian day 135 and 148, respectively, are shown in Figure 7. During this time, sea ice surface temperatures decreased from −17°C to −29°C, and the upper layer of core A3C9 was approximately

**Table 3.** Summary of Experiment 3

| Sample | Date of Sampling, Julian days | Ice Thickness, cm | Latitude, °S | Longitude, °W |
|---|---|---|---|---|
| A3C1 | 78 | 42 | 70.4 | 53.4 |
| A3C2 | 85 | 53 | 69.8 | 53.7 |
| A3C3 | 93 | 63 | 68.9 | 53.5 |
| A3C4 | 100 | 68 | 68.7 | 55.5 |
| A3C5 | 110 | 70 | 68.4 | 53.1 |
| A3C6 | 117 | 73 | 68.4 | 52.7 |
| A3C7 | 125 | 78 | 67.9 | 53.4 |
| A3C8 | 135 | 81 | 67.6 | 53.2 |
| A3C9 | 148 | 87 | 66.2 | 52.9 |
| A3C10 | 159 | 97 | 65.8 | 52.7 |

During Experiment 3, surface seawater temperature, salinity, silicate, and chlorophyll *a* concentrations ranged from −1.85 to −1.83°C, 34.06 to 34.42 psu, 2000 to 1450 $\mu g/L$, and 0.047 to 0.001 $\mu g/L$, respectively. Eighteen diatom species were found in surface seawater with six species, *Fragilariopsis vanheurckii, F. cylindrus, F. separanda, F. curta, Corethron criophilum*, and *Manguinea rigida*, being dominant, i.e., occurring as >30% of the total number of cells.

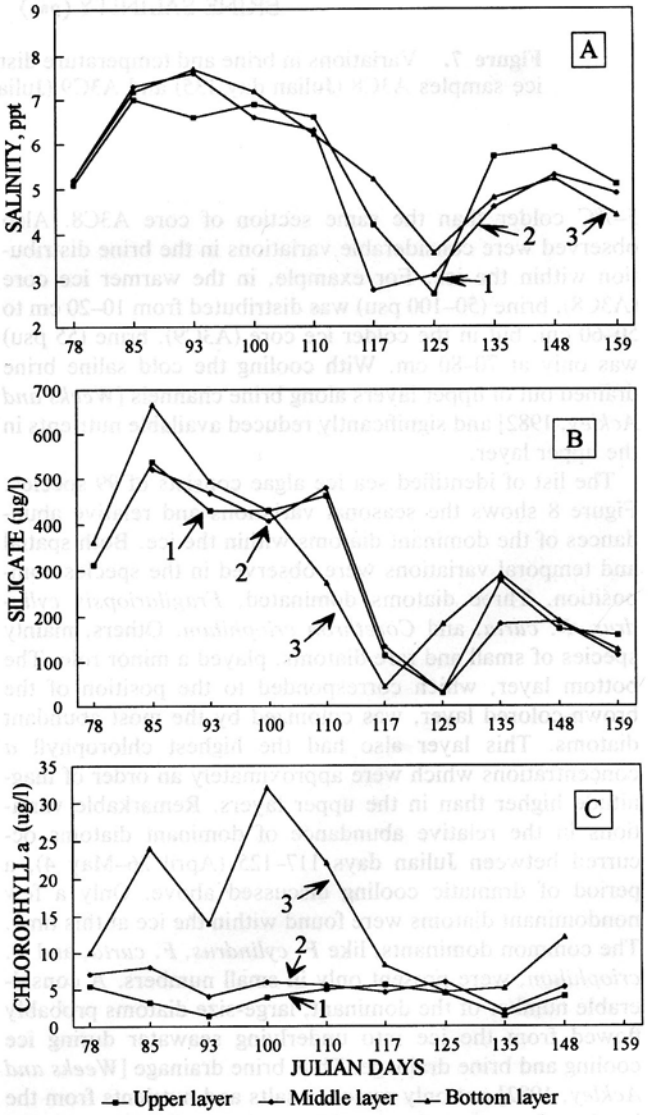


**Figure 6.** Variations of (a) salinity, (b) silicate, and (c) chlorophyll *a* concentrations in the upper (line labeled 1), middle (line labeled 2), and lower (line labeled 3) layers of growing young sea ice forming on the lead during March–June 1992 (experiment 3).

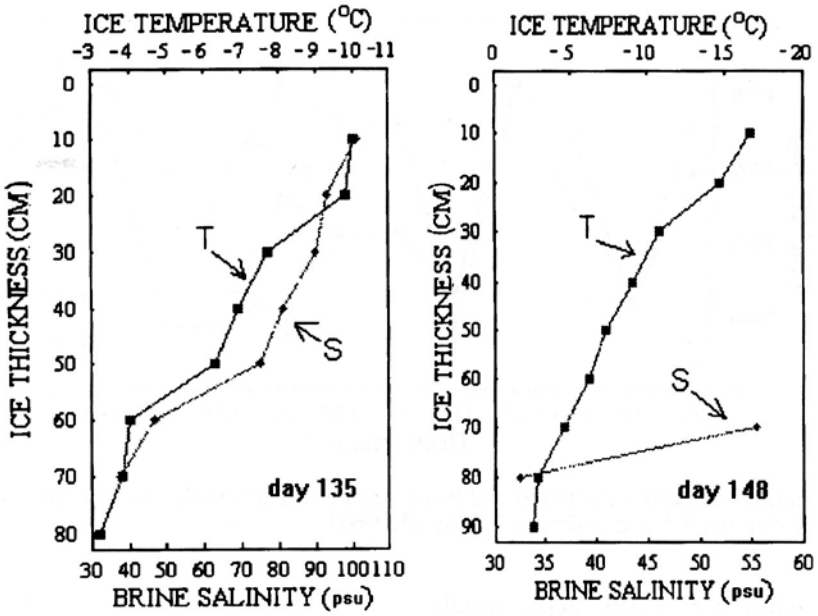


**Figure 7.** Variations in brine and temperature distribution within the thickness of the growing young sea ice samples A3C8 (Julian day 135) and A3C9 (Julian day 148).

5–7°C colder than the same section of core A3C8. Also observed were considerable variations in the brine distribution within the ice. For example, in the warmer ice core (A3C8), brine (50–100 psu) was distributed from 10–20 cm to 50–60 cm, but in the colder ice core (A3C9), brine (55 psu) was only at 70–80 cm. With cooling the cold saline brine drained out of upper layers along brine channels [*Weeks and Ackley*, 1982] and significantly reduced available nutrients in the upper layer.

The list of identified sea ice algae consists of 99 species. Figure 8 shows the seasonal variations and relative abundances of the dominant diatoms within the ice. Both spatial and temporal variations were observed in the species composition. Three diatoms dominated, *Fragilariopsis cylindrus*, *F. curta*, and *Corethron criophilum*. Others, mainly species of small and rare diatoms, played a minor role. The bottom layer, which corresponded to the position of the brown-colored layer, was colonized by the most abundant diatoms. This layer also had the highest chlorophyll *a* concentrations which were approximately an order of magnitude higher than in the upper layers. Remarkable variations in the relative abundance of dominant diatoms occurred between Julian days 117–125 (April 26–May 4), a period of dramatic cooling discussed above. Only a few nondominant diatoms were found within the ice at this time. The common dominants, like *F. cylindrus*, *F. curta*, and *C. criophilum*, were present only in small numbers. A considerable number of the dominant, large-size diatoms probably flowed from the ice into underlying seawater during ice cooling and brine drainage. Thus brine drainage [*Weeks and Ackley*, 1982] not only removes salts and nutrients from the ice, but also suspends materials, such as cells. Accordingly, brine drainage likely plays an ecologically important role during winter with regard to food sources for the invertebrate animals associated with the underlying sea ice surface and with the Antarctic sea ice ecosystem as a whole.

## 4. Discussion

On the basis of three in situ experiments conducted on leads with young growing sea ice it is possible to assess the physical-chemical-biological interactions in areas of open water during the austral winter.

Short- and long-term variations observed within growing sea ice were controlled both by meteorological factors and brine drainage mechanisms. The phenomenon of liquid migrating through the ice has received considerable attention in the literature [*Whitman*, 1926; *Untersteiner*, 1968; *Tsurikov*, 1976]. It is well known that a temperature gradient in sea ice establishes salt rejection from the cold, saline upper layer of ice to the warmer, less saline lower layer. This process is called brine expulsion, and its removal of brine from sea ice to seawater was explored by *Untersteiner* [1968], *Lake and Lewis* [1970], and *Cox and Weeks* [1988]. However, because both brine pocket migration and brine expulsion were not sufficiently strong processes to explain the observed extreme changes in the salinity profiles (Figure 7), these results were better explained by a brine gravity drainage mechanism. This mechanism was driven by meteorological factors, mainly extreme changes in air surface temperatures between Julian days 129 and 148 (Figure 2), which, in turn, affected the ice surface temperature (Figure 7). Warmer ice (i.e., core A3C8) was very soft because of brine (100 psu) in the upper 10–20 cm, while in colder ice, brine was expelled from the upper to the lower layers and brine salinity decreased to 55 psu in the 70- to 80-cm layer. While Scuba diving under the newly formed ice, during this period, active brine drainage was often observed from the ice sheet into the underlying sea water. Gravity drainage of cold dense brine into seawater also stimulated the formation of stalactites on the bottom surface of the ice. The same phenomenon has been observed in McMurdo Sound [*Dayton and Martin*, 1971].

Gravity drainage is the dominant mechanism in young

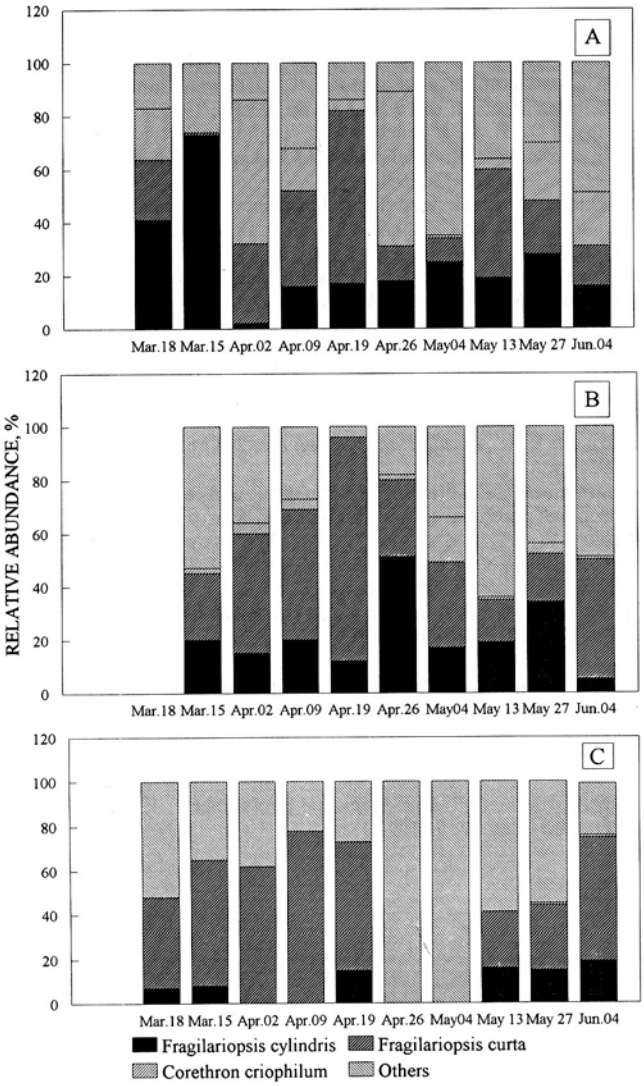


**Figure 8.** Seasonal variations in relative abundance of the dominant diatoms species in the (a) upper, (b) middle, and (c) lower layers of growing young sea ice on the lead during March–June 1992.

growing sea ice [*Untersteiner*, 1968]. As the ice sheet grows and its surface rises farther above sea level, a pressure head develops in the intercrystal brine system, driving the underlying brine out of the ice [*Eide and Martin*, 1975] through vertical tubular channels [*Martin*, 1974; *Eide and Martin*, 1975; *Niedrauer and Martin*, 1979]. Brine drainage from the channels is oscillatory, with the duration of downward flow being shorter than the duration of upward flow. Oscillations occur because the brine level inside the ice moves between two positions of hydrostatic equilibrium. When the cold, dense brine from the upper layer of the ice fills the brine channels, the equilibrium brine level is lower than when warmer, and less saline sea water fills the channel. This small mass perturbation results in a large pressure imbalance within the brine drainage tube, which accelerates seawater up the tube until the second higher equilibrium level is reached. The seawater is then cooled, and the process is repeated [*Martin*, 1974]. Oscillatory periods of approximately 1 hour with a 1:4 ratio of inflow and outflow have been described for growing artificial sea ice [*Eide and Martin*, 1975]. Results from this study indicate a 1.5- to 2-hour oscillatory period with 1- to 1.5-hour inflow and 0.5-hour outflow of brine in a 6- to 8-cm skeletal layer of 28-cm thick young ice (experiment 3), an oscillatory period about twice as long as that described by *Eide and Martin* [1975]. These processes are especially important when considering periodic changes in the nutrient environment of ice algal communities.

Incorporation of microorganisms into sea ice occurred throughout its growth. During the initial stages of ice formation, e.g., the first 24 hours of experiment 1, there was probably a period of mechanical harvesting of plankton cells from the seawater. Under these quiescent conditions the significant enrichment of phytoplankton in initial stages of ice growth was not detected as has been shown for frazil ice growth under turbulent conditions [*Clarke and Ackley*, 1984]. Because the winter phytoplankton population was very poor, few cells were incorporated into the ice sheet during ice formation. Colonization by microorganisms may have resulted from incorporation of cells into the crystal structure during brine oscillation processes in the bottom 6- to 8-cm skeletal layer of the ice (experiment 2). Chlorophyll *a* concentrations increased when the ice thickness was 30–40 cm, but this algal growth was most favorable within the bottom part of the congelation ice and very close to the skeletal layer, where seawater rich with nutrients was transported to the cells through brine channels during the oscillation processes. Chlorophyll *a* concentrations in the lower ice layers were about 10 times higher than in the upper layers and 100–1000 times higher than in the underlying seawater (Figure 6 and Table 3). Photosynthetic rate experiments with ice algae incubated for 24 hours [*Sullivan et al.*, 1992] showed net fixation of $^{14}C$ bicarbonate and indicated that ice algae were physiologically active in winter despite subzero temperatures. This result was supported by an in situ increase in algal biomass as determined by chlorophyll *a* (experiment 3). It is very important to note that the net increase in ice algal biomass did not result from the sequestering of phytoplankton during new ice formation but from photosynthesis and growth of ice algae. These results, some of the first pelagic data of the austral autumn/winter ecosystem in young ice, may be used to provide initial conditions or constraints in future models of the Southern Ocean ecosystem.

**Acknowledgments.** I am grateful to Steve Ackley, CRREL, to Chris Fritsen and Calvin Mordy, USC, for help, collaboration, and support during the field ice observations at ISW, and to my co-diver Vladimir Grichenko, AARI, for assistance and help during the risky under ice diving. Special thanks are due to C. W. Sullivan, former director of the Hancock Institute of Marine Studies, USC, for scientific support and continued enthusiasm. This research was supported by the Russian Foundation for Basic Research under grant 94-05-16707.

## References

Ackley, S. F., G. Dieckmann, and H. Shen, Algal and foram incorporation into new sea ice (abstract), *Eos Trans. AGU*, *68*, 1736, 1987.

Bartsch, A., Sea ice algae of the Weddell Sea (Antarctica): Species composition, biomass, and ecophysiology of selected species, *Ber. Polarforsch.*, *63*, 110 pp., 1989.

Bunt, J. S., and E. J. F. Wood, Microbiology and Antarctic sea ice, *Nature*, *199*, 1254–1255, 1963.
Burkholder, P. R., and E. F. Mandelli, Productivity of microalgae in Antarctic sea ice, *Science*, *149*, 872–874, 1965.
Clarke, D. B., and S. F. Ackley, Sea ice structure and biological activity in the antarctic marginal ice zone, *J. Geophys. Res.*, *89*, 2087–2095, 1984.
Cox, G. F. N., and W. F. Weeks, Profile properties of undeformed first-year sea ice, *Res. Rep. 88-13*, Cold Reg. Res. Eng. Lab., Hanover, N. H., 1988.
Dayton, P. K., and S. Martin, Observation of ice stalactites in McMurdo Sound, Antarctica, *J. Geophys. Res.*, *76*, 1595–1599, 1971.
Eide, L. I., and S. Martin, The formation of brine drainage features in young sea ice, *J. Glaciol.*, *14*, 137–154, 1975.
Garrison, D. L., and K. R. Buck, Sea ice algae in the Weddell Sea, 1, Biomass distribution and the physical environment (abstract), *Eos Trans. AGU*, *63*, 47, 1982.
Gordon, A. L., and V. V. Lukin, Ice Station Weddell #1, *Antarct. J. U. S.*, *27*, 97–99, 1992.
Hoshiai, T., Seasonal change of ice communities in the sea ice near Syowa Station, Antarctica, in *Polar Oceans*, edited by M. J. Dunbar, pp. 307–317, Arctic Institute of North America, Calgary, Alberta, Can., 1977.
Kisilev, I. A., *Plankton of Seas and Continental Basins*, vol. 1, 657 pp., Nauka, Leningrad, 1969.
Lake, R. A., and E. L. Lewis, Salt rejection by sea ice during growth, *J. Geophys. Res.*, *75*, 583–590, 1970.
Martin, S., Ice stalactites: Comparison of a laminar flow theory with experiment, *J. Fluid. Mech.*, *63*, 51–79, 1974.
Meguro, H., Plankton ice in the Antarctic ocean, *Antarct. Rec.*, *14*, 1192–1199, 1962.
NASA, *Antarctic Sea Ice, 1973–1976: Satellite Passive Microwave Observations*, Washington, D. C., 1987.
Niedrauer, T. M., and S. Martin, An experimental study of brine drainage and convection in young sea ice, *J. Geophys. Res.*, *84*, 1176–1186, 1979.
Scientific Committee on Oceanic Research-UNESCO, Monographs on oceanographic methodology, 1, Determination of photosynthetic pigments in sea water, 69 pp., Paris, 1966.
Smith, S. D., R. D. Muench, and C. H. Pease, Polynyas and leads: An overview of physical processes and environment, *J. Geophys. Res.*, *95*, 9461–9479, 1990.
Strickland, J. D. H., and T. R. Parsons, *A Manual of Sea Water Analysis*, 311 pp., Fisheries Research Board of Canada, Ottawa, Ont., 1968.
Sullivan, C. W., and A. C. Palmisano, Sea-ice microbial communities in McMurdo Sound, *Antarct. J. U.S.*, *16*, 126–127, 1981.
Sullivan, C. W., C. H. Fritsen, and C. W. Mordy, Time series studies of microbial production in Antarctic pack ice at the U.S.-Russian drifting ice station, ISW-1, in the western Weddell Sea (abstract), *Eos Trans. AGU*, *73*(43), Fall Meeting Suppl., 300, 1992.
Tsurikov, V. L., *Liquid Phase in Sea Ice*, 210 pp., Nauka, Moscow, 1976.
Untersteiner, N., Natural desalination and equilibrium salinity profile of perennial sea ice, *J. Geophys. Res.*, *73*, 1251–1257, 1968.
Weeks, W. F., and S. F. Ackley, The growth, structure, and properties of sea ice, *CRREL Monogr.*, *82-1*, Cold Reg. Res. Eng. Lab., Hanover, N. H., 1982.
Whitman, W. G., Elimination of salt from sea water ice, *Am. J. Sci., Ser. S 11* (62), 126 pp., 1926.

I. A. Melnikov, P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Krasikova, 23, 117218 Moscow, Russia.

(Received January 18, 1994; revised September 7, 1994; accepted September 7, 1994.)