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FREEZING DRIVEN UPWELLING IN ANTARCTIC SEA ICE BIOLOGICAL SYSTEMS

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Abstract: Within existing ice covers, we found fluid motion can also be driven by freezing-induced convection. Surface snow-slush and near-surface highly porous layers were found in the pack ice at Ice Station Weddell in the western Weddell Sea at end of summer and examined for physical and biological processes. Convective fluid motion, driven by brine rejection from the ice freezing from above as air temperatures dropped, replaced nutrient depleted waters in the layers with nutrient rich sea water from below. The upwelling nutrients fueled autumn blooms of algae in second-year ice in the near surface regions of the ice cover where sufficient light is also available. Both the timing and location of these blooms within the ice cover are unlike the bottom spring blooms of sea ice algae previously observed.

1. Introduction

Fluid dynamic processes related to sea ice contribute directly to biological processes in several distinctive ways. Initially, biological material is physically incorporated in growing sea ice covers through scavenging of particulates as ice crystals are moved through the water column, or by the circulation and wave pumping of particulate laden sea water through loose aggregations of frazil ice. Sea ice is a two-phase material, containing sea water inclusions enriched in salts and nutrients, and therefore provides a microenvironment suited for marine organisms, if they can physically fit in the spaces available, tolerate cold, and adapt to the saline and light changes typical of the ice cover (ACKLEY and SULLIVAN, 1994; EICKEN, 1992). Ice habitats are divided into three basic categories, those found at the top surface, in the interior, or at the bottom surface of the ice (HORNER *et al.*, 1992; HORNER, 1985). The physical conditions of the ice cover determines the type of habitat and therefore the type of biological community that develops.

This paper first briefly reviews the types of communities that have been observed in Antarctic sea ice. We then discuss two field experiments. These are, respectively, surface and near-surface porous layer biological communities that were observed during Ice Station Weddell (February–June, 1992) (GORDON, 1993).

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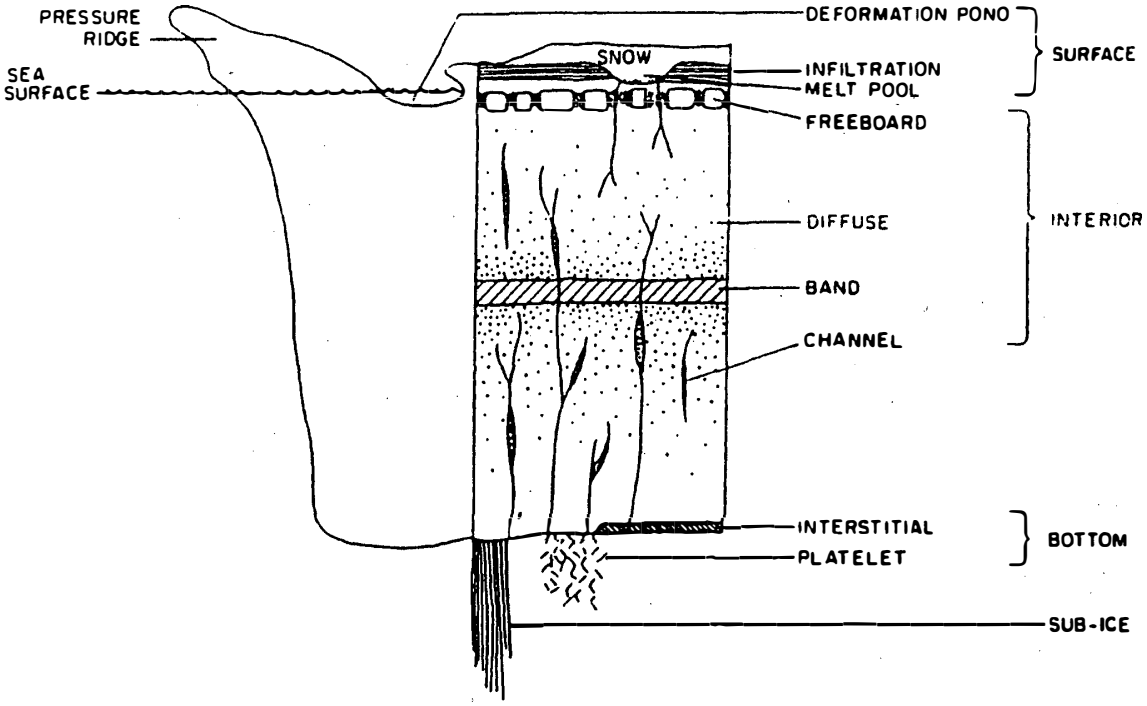


Fig. 1. Surface, interior and bottom habitats in sea ice (after HORNER et al., 1992).

Sea ice biological habitats

Figure 1, after HORNER *et al.* (1992), shows schematically the ice habitats and their locations within the ice cover (with the stipulation that not all habitats shown are present at the same time in the ice cover).

a) Surface communities

Surface communities develop in slush pools created by the flooding (infiltration) of the snow cover at the top surface of the Antarctic sea ice cover. The processes causing surface flooding are: snow load depression of the ice cover, and ice ridge loading on the surface (ACKLEY and SULLIVAN, 1994; LANGE and EICKEN, 1991). Depression of the ice surface by either type of loading can lower the top ice surface below sea level, followed by infiltration of sea water into the snow through cracks or pores in the ice. The sea water can contain a seed population of organisms as well as the nutrients necessary to sustain photosynthesis, given sufficient light. These communities then bloom in the higher light available near the top surface of the ice (compared to the underice environment), and can give it a distinct color because of the high concentration of organisms that develops. Snow ice, and therefore, this biological community, are common over widespread areas of the Antarctic sea ice (MEGURO, 1962; BURKHOLDER and MANDELLI, 1965; ACKLEY and SULLIVAN, 1994). LEGENDRE *et al.* (1992) estimate half the area of Antarctic pack ice (10×10^6 km^2) have snow ice derived communities.

b) Interior communities

Two main interior communities have been identified, frazil ice communities that develop during ice formation and the freeboard or porous layer community observed in older ice (ACKLEY *et al.*, 1979; GARRISON *et al.*, 1983; GARRISON *et al.*, 1986; ACKLEY and SULLIVAN, 1994). The frazil ice communities were first discovered in newly forming pancake ice in Antarctica where concentration levels of marine organisms were found to

be ten to one hundred times that found in the underlying water (GARRISON *et al.*, 1983; CLARKE and ACKLEY, 1984). Nutrient levels in the newer ice were however, similar to that of surface sea water (GARRISON *et al.*, 1983; GARRISON *et al.*, 1990; DIECKMANN *et al.*, 1991) when scaled to the salinity of the ice. Since nutrients were not depleted, these authors concluded that physical incorporation of the algae, rather than biological growth, was responsible for the higher concentrations. Two mechanisms, wave pumping of sea water in and out of newly forming ice on the surface (ACKERMANN *et al.*, 1994), and, scavenging of organisms by individual ice crystals (ACKLEY, 1982; GARRISON *et al.*, 1983), have been suggested to account for the concentrating of organisms in the ice by physical entrapment.

The second interior community, the freeboard layer community, can start a few cm below the ice surface and continues to mid-depths into the ice interior, but only in ice that lasts well into the summer period (ACKLEY and SULLIVAN, 1994; ACKLEY *et al.*, 1979; BUCK and SULLIVAN, 1990). This layer, characteristically rich in biology, is a porous structure of partially rotted ice and sea water freshened by ice melt in $>50\%$ concentration. The layer may develop through a biophysical feedback process (ACKLEY and SULLIVAN, 1994; EICKEN *et al.*, 1991). These authors postulate that biological organisms (dark color) absorb solar radiation in this near surface layer, causing some heat trapping and melting of the ice, followed by intrusion of sea water through the holes and gaps created by the melting. Nutrients brought in with the sea water then further contribute to the algal bloom. If the ice lasts through the summer period, a second algal bloom can occur in the freeboard layer during the fall freeze-up period resulting in an internal band (Fig. 1).

c) Bottom communities

Bottom communities form either in the dendrite structure at the base of columnar ice, or in the platelet layer, a loose unconsolidated aggregate of ice discs or platelets, found beneath ice in coastal regions near Antarctic ice shelves. Since the overlying ice (up to 2 m thickness) limits the light penetrating to the base of the ice, the bottom community develops in the fall and spring seasons when incident total light levels are so high that the small fraction that is transmitted is sufficient to sustain photosynthesis by algae (ACKLEY and SULLIVAN, 1994). Unlike the coastal zone, where strong winds can scour the upper surface free of snow, the drifting pack ice usually has a thicker snow cover. Although columnar ice (with its basal dendrite structure) is relatively prevalent in the drifting pack zone, this other factor, the depth of the snow cover, apparently limits the light that can penetrate to the base of the ice, so the bottom biological community is not observed to accumulate to the same levels, nor is primary production rate in the drifting pack as high as it is in the fast ice coastal zone of Antarctica (DIECKMANN *et al.*, 1991; FRITSEN *et al.*, 1994).

2. Field Experiments

Two sites, (A and B) were established in the drifting pack ice zone of the western Weddell Sea on the camp floe of Ice Station Weddell (GORDON, 1993) during February 1992 as part of an array to investigate the heat balance of the ice cover (LYTLE and ACKLEY, 1995). These two sites were monitored and the subject of joint physical-

biological investigations of the ice cover, as the station drifted northward at 53°W longitude from 71.4°S latitude (9 February) to 65.8°S (6 June) (FRITSEN *et al.*, 1994). The two sites, although located on the same floe, had undergone different formation histories and differed in their morphological, ice thickness and snow cover characteristics as described below.

At each site, we placed a rod mounted with thermistors, at 5–20 cm vertical spacings, from the air into the snow and ice covers and further into the underlying sea water. Temperatures were recorded once per hour throughout the experiment (~100 days) although site A had two five day data gaps from day 110 to 115 and day 120 to 125, (where 1 January=day 1). Snow properties (density, crystal sizes and types, salinity) from snow pits and horizontal profiles of snow depth and elevation (relative to sea level) were collected. These profiles, with ice thickness measurements, were taken from site A, as it was moderately rough and showed higher variation in ice thickness and surface roughness than site B. Two to four ice cores were taken periodically (week to ten day intervals) through the experimental period for each site and analyzed for ice physical and biological properties, including crystal texture, salinity, chlorophyll *a*, and nutrients, as well as providing some ice thickness measurements at site B. Brine sampling from porous layers (found early in the experiment) was made by using a large syringe to extract the fluid from a pit or hole made to the porous layer within the snow or ice cover. Salinity was determined by conductivity of the brine or ice core melt water using a Beckman conductivity meter, calibrated to sea water salinity composition. Typically samples were cut from cores at 10 cm intervals for physical and chemical proterties and at 20 cm intervals for chlorophyll *a* and phaeopigments. Chlorophyll *a* was determined fluorometrically and nutrients by autoanalyzer using methods described in PARSONS *et al.* (1984).

3. Results

3.1. Site A

a) Ice and snow thicknesses

As shown in Fig. 2, (a profile of snow and ice thicknesses and elevations measured on day 56 (February 25)), site A consisted of deformed ice with an average thickness of 1.44 m (st. dev. ±0.42 m). About 80% of the points sampled had an ice surface below sea level and were flooded at the base of the snow cover, with a brine/snow slush mixture, just above the snow-ice interface. As the season progressed into winter, the slush froze; and from a surface elevation and snow depth profile taken on day 112 (Fig. 3), only 22% of the ice surface was below sea level. Between the two dates the snow elevation, from accumulation, increased by 5 cm . The snow depth, including the slush, initially averaged 57 cm over the profile line on day 56 but, instead of increasing from accumulation (to 62 cm), it decreased in depth to 44 cm as a result of slush freezing to ice by day 112. We estimate then that an average of 18 cm of slush (62 cm–44 cm) froze into saline snow ice between the two dates. The preponderance of the ice thickness change was due to the freezing of the slush, as typically ice of the average thickness indicated (>1.4 m) showed little bottom freezing, as estimated from lower thermistor string and ice bottom accretion/ablation measurements made in the area (LYTLE and

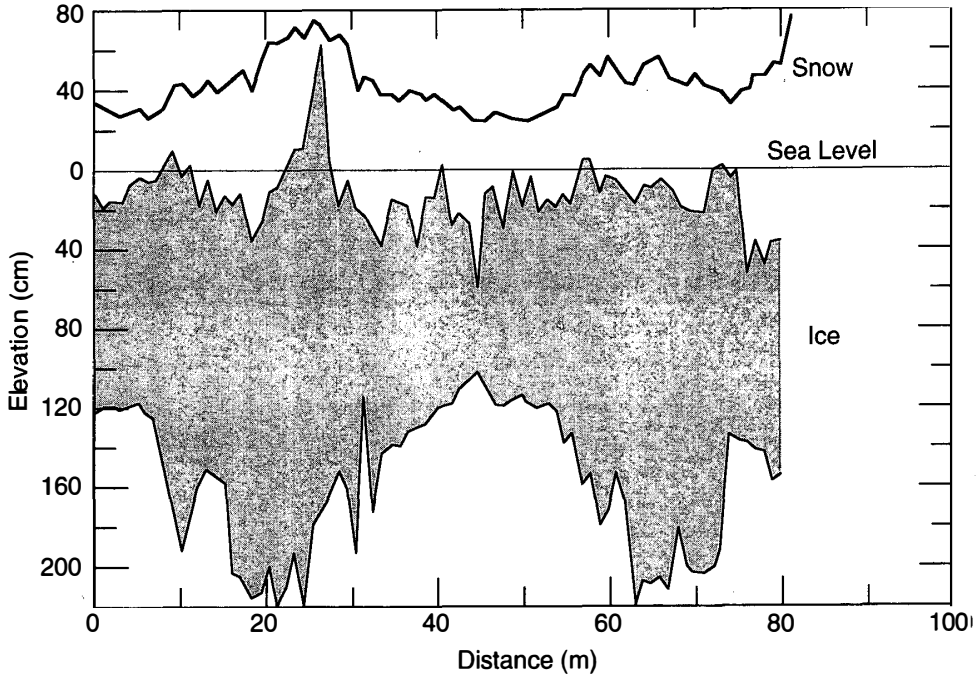


Fig. 2. Snow Elevation, Depth and Ice Thickness profile from site A on the Ice Station Weddell (ISW) floe, obtained on February 25, 1992 (day 56).

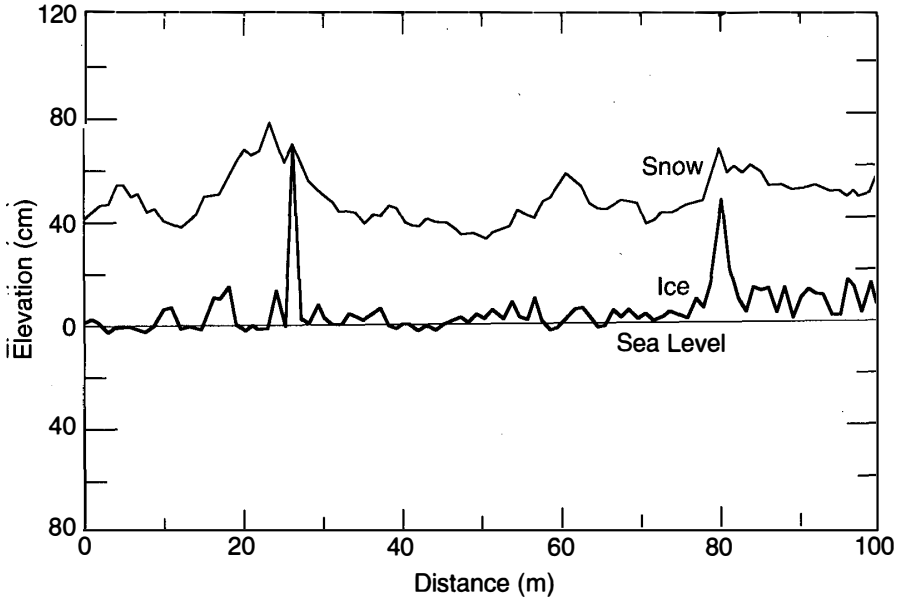


Fig. 3 Snow Elevation and Depth profile from site A on the Ice Station Weddell (ISW) floe, obtained on April 21, 1992 (day 112). The line is over the same profile previously taken and shown on Fig. 2.

ACKLEY, 1995; A. MAKSHTAS, V. CHURUN, and V. GRISCHENKO, personal commun.).

b) Ice and snow-slush properties

From liquid samples drawn from the slush layer at site A, an initial brine salinity (day 56) of 31.5 psu was measured. This value increased by 3.8 psu to 35.3 psu (day 77) when the freeze-up was underway. We estimate that the layer consisted of about 50% ice crystals and 50% brine, resulting in a bulk salinity of about 16 psu. Later in the

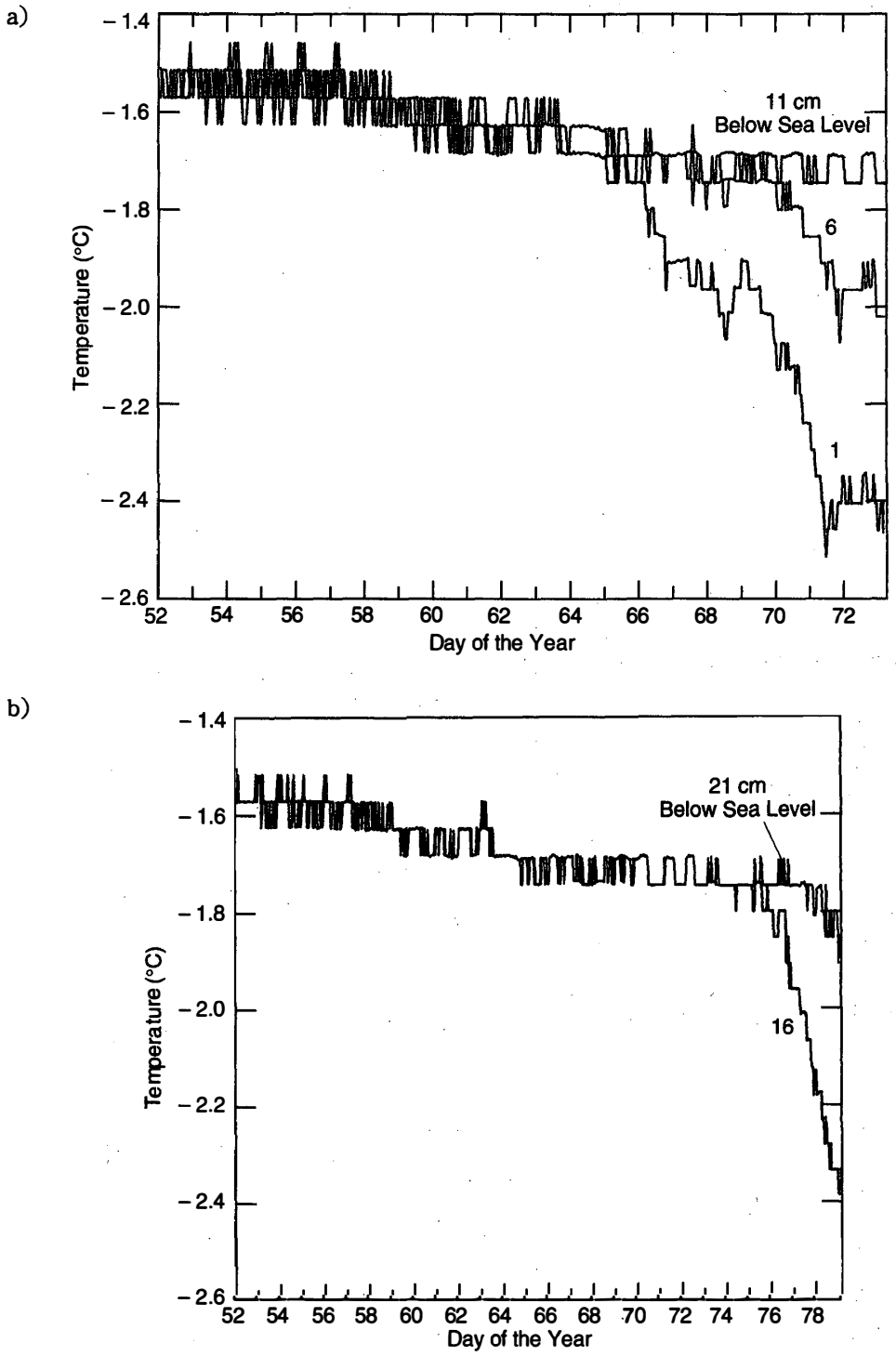


Fig. 4. a) Time series of slush layer temperatures (1, 6 and 11 cm below sea level) at site A during the freezeup period. Drops in the 11 cm level are of the order of 0.2°C, corresponding to salinity increases in the layer (3.6 psu) because of brine rejected by ice formation above this level.

b) Time series of temperatures below the slush layer (16 and 21 cm below sea level). The drop in temperature on days 77 (16 cm level) and 78 (21 cm level) concur with the freezing front passing the 11 cm level on about day 75 indicating the bottom of the slush layer (assumed at that level) was frozen at that time.

winter, after this layer had completely frozen, the bulk layer salinity was reduced from 16 psu to 6 psu, as obtained from ice cores, *i.e.* it desalinated through the thick ice below it.

c) Ice temperatures

The thermistor string at site A was located near the end of the profile line and initially had an ice thickness of 110 cm and a snow thickness of 40 cm. A snow pit taken near the site indicated slush at the base of the snow cover, as typically seen for the thinner ice in the profile line (Fig. 2). Since the snow elevation (above sea level) was 34 cm at the site, we estimate >6 cm of snow-slush at the thermistor site. Time series of temperatures from site A are shown for the initial part of the experiment in Fig. 4a. The temperatures in the slush layer decreased about 0.2 ℃ from day 56 to day 66 as the slush layer began to freeze and the brine was rejected. Salt rejection during ice growth increases the brine salinity and therefore decreases the freezing point temperature in the layer. The temperature decrease shown is equivalent to an increase in salinity of about 3.6 psu, in good agreement with the measured salinity change from the drawn samples (3.8 psu). After day 66, the temperatures then remained at about -1.8 ℃. Temperatures below the slush layer sequentially decreased below -1.8 ℃ (thermistors at 16 and 21 cm below sea level, Fig. 4b) after day 75, showing the slush layer above these depths had frozen between days 60 and 75.

d) Ice biological community

Figure 5 shows the temporal change in the ice concentration of chlorophyll *a* (contours are in $\mu g\, l^{-1}$) from ice cores taken before the freezeup on day 56 and well after it until day 158. Typically three cores were taken every week or ten days for this determination, and sampled at 10 to 20 cm intervals over the length. The top layer concentration has increased by ten fold from 2 to $>20\, \mu g\, l^{-1}$, a measure of the bloom in the slush layer. The bloom also continues downward in the ice with the largest chlorophyll *a* increases shown at depths 25 to 50 cm down from the surface. Figure 6

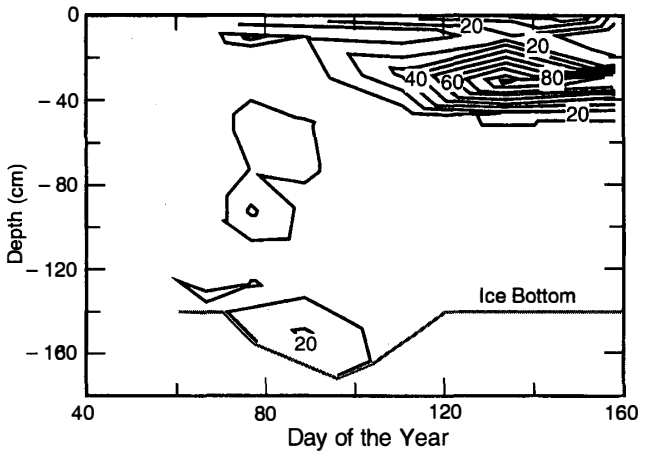


Fig. 5. Depth-time profiles of chlorophyll a (contours in μg l^{-1}) in the sea ice at site A from days 56 to 158. Increases in the levels are seen near the top few cm and further down (50 cm) in the cores indicating the algal bloom in the near-surface layer.

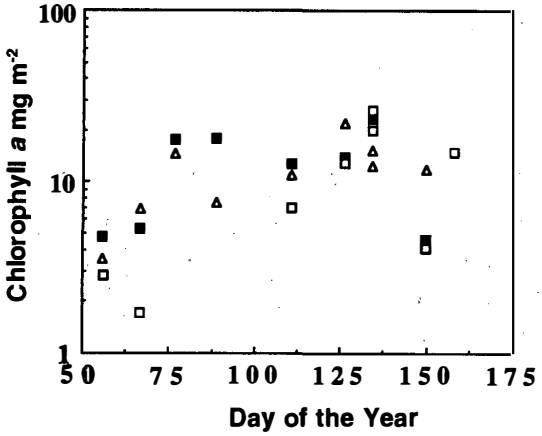


Fig. 6. Standing crop time series, or depth-integrated chlorophyll a concentration (mg m^{-2}), from cores taken at site A. Closed squares are for cores melted in filtered sea water, open for cores melted directly (both chlorophyll a determined fluorometrically) and triangles refer to spectrophotometric determination of chlorophyll a from direct melt. Each symbol refers to a whole core integration, and each day is for cores taken within 1 m of each other.

shows the series of standing crop increases (depth integrated chlorophyll *a* concentration) for site A cores. Samples taken after the freezeup period (day 70) showed 3 to 10 fold higher crops than before, indicating the bloom takes place in the ice during and following the slush layer freezeup. Some differences found between the cores in total biomass are attributed to the horizontal variability of the site, which differed in the thickness of snow cover, slush layer, and ice from point to point as shown on Fig. 2, as well as the timing during the freezeup process. Still, increases in total chlorophyll *a* with time, as given by the core data, reflect that the biological growth occurred throughout the site during and shortly after the slush freezeup period, as the minimum values of chlorophyll *a* were found primarily in the earliest stages, just prior to the freezeup period.

3.2. Site B

a) Ice and snow thicknesses

Site B was located in an undeformed section of ice that had also lasted through the summer season. The site was about 40 m from the floe perimeter. The ice thickness, measured from cores and from the edge of a crack that came through the region (in late March), was 1.1 m (st. dev. $\pm$0.10 m). The standard deviation of ice thickness of 10 cm, compared to 40 cm for site A is an indication of the less deformed and flatter nature of this site. At the site B thermistor string, the initial snow depth was 17 cm and ice thickness was 120 cm. The snow depth variation was much less than at site A, varying only a few cm vertically over tens of meters horizontally.

b) Ice and snow properties

In the snow pit measured on day 58, a snow salinity of 1 psu was measured at the bottom of the pit, just above the snow-ice interface, probably due to wicking up of brine from the ice surface at the warm temperatures observed. No measurable salinity was found in later snow pits. At site B an ice core collected on day 60 showed a porous layer, from about 2 cm above to 20 cm below sea level (Fig. 7). Seven cm of granular sea ice was found above this saturated porous layer and the layer contained larger ice aggregates than individual snow grains. Because our observations started after some sub-freezing air temperatures had occurred it is currently unclear whether this layer originated as a a flooded snow layer, undergoing some refreezing, or as a freeboard porous layer that originated as deteriorated sea ice from internal melting as briefly

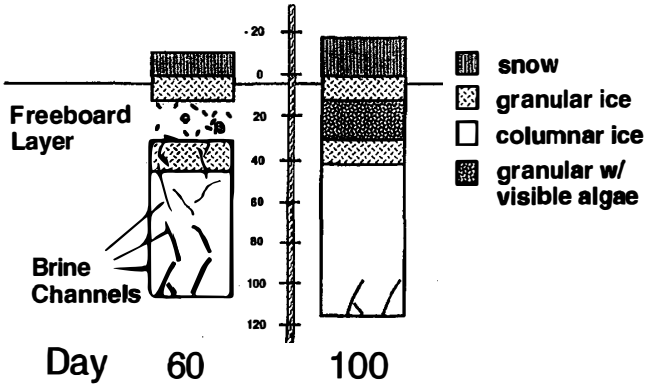


Fig. 7. Structural cartoons from ice core profiles taken at site B on days 60 and day 100. The porous layer shown on day 60 was frozen as granular sea ice on day 100, approximately coinciding with a visible band of algae at that same vertical location within the core.

described above (ACKLEY and SULLIVAN, 1994). At site A the slush layer was clearly differentiated from the snow-ice interface and extended upward into snow, while at site B the layer started below the surface of the ice, at the time of observation (Fig. 7). Undeformed columnar ice of 62 cm underlay this granular ice and porous layer, and 1–2 cm diameter vertical channels were observed in the underlying ice.

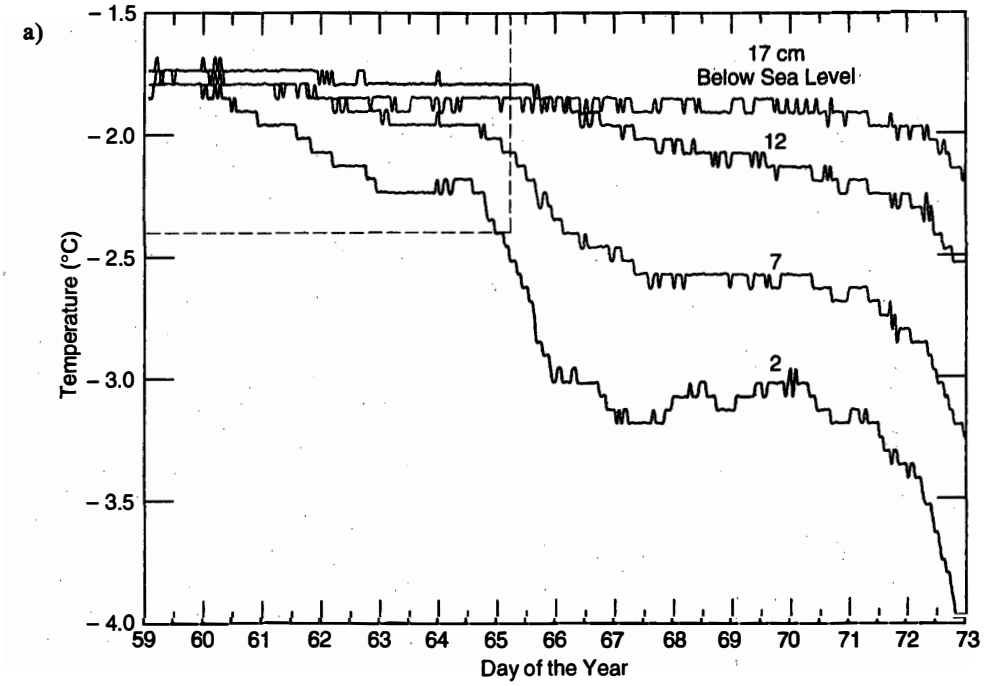
The initial salinity of the brine in the porous layer at site B was 35 psu. We estimated that the layer was composed of 50% ice and 50% brine initially, although this is approximate because of the presence of the irregular chunks of sea ice aggregates in the porous layer. The bulk salinity of the layer was then estimated at 18 psu. Ice core profiles indicated this layer desalinated to a salinity of 6 psu as it froze, a similar salinity value to that of the frozen slush layer at site A.

c) Ice temperatures

Figure 8a shows the temperature through the site B porous layer as freezing occurred. Smaller temperature changes (0.05 to 0.1℃) were observed in the lower thermistors in the porous layer (Fig. 8b) at this site than in the slush layer at site A (0.2 ℃). These values give a change in salinity of the water of about 1 psu, suggesting that the brine rejected increased the salinity of the sea water to 35 to 36 psu initiating overturning and bringing in sea water from below the ice. The sharp decline in temperature of the top thermistor (bottom line Fig. 8a) follows closely a similar sharp change in air temperature on day 64, increasing the freezing rate of the layer. Freezing of the layer was essentially completed by days 75 to 80, (shown by temperatures < -2 ℃, Fig. 8a) about two to three weeks after the freezing front passed the top of the layer. Temperatures in the lower portions of the layer stayed at -1.8 to -1.9℃ when still unfrozen, corresponding to the freezing point for these slightly elevated salinities above the ambient sea water.

d) Ice biological community

While salinity in the porous layer water was slightly elevated above the initial condition from brine rejection, Fig. 9 shows two of the nutrients were, instead, highly elevated after day 65, relative to the initial values measured before day 60 when the freezing of the layer had not started. These higher nutrient values were typical of



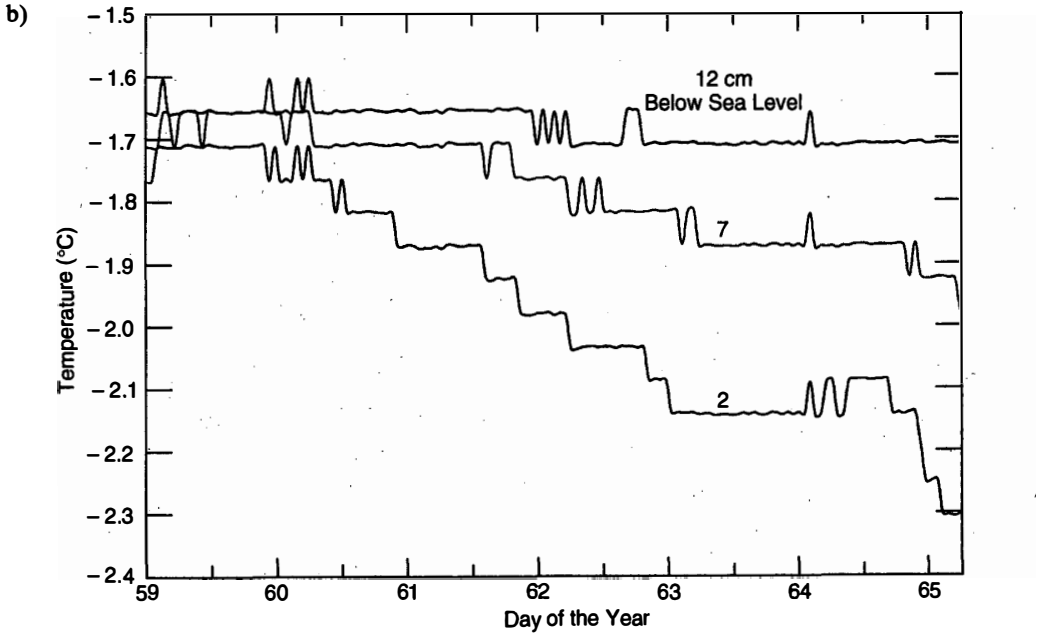


Fig. 8. a) Time series of porous layer temperatures at site B (thermistors at 2, 7, 12 and 17 cm below sea level). Freezeup of the porous layer was completed approximately on day 75, coinciding with the desalination of the porous layer (FRITSEN et al., 1994), although high biological growth apparently continued below this level for a longer period (Fig. 10). The dashed box indicates the records shown in detail in Fig. 8b.

b) Time series of temperatures from thermistors showing the temperature change (0.05 to 0.1°C) in the porous layer at site B. The decreased temperatures as the layer salinates correspond to salinities of 35 to 36 psu at the freezing point.

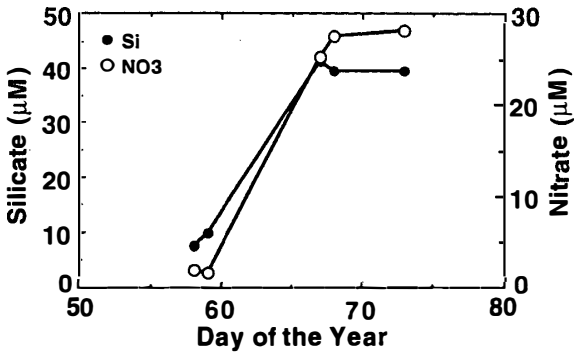


Fig. 9. Nutrients, nitrate and silicic acid (NO_3 and $Si(OH)_4$) in the porous layer at site B, as a function of time. The elevated levels are similar to values from underice sea water, indicating exchange of the nutrient-depleted waters within the ice with surface sea water, driven by density increases in the waters induced by freezing from above.

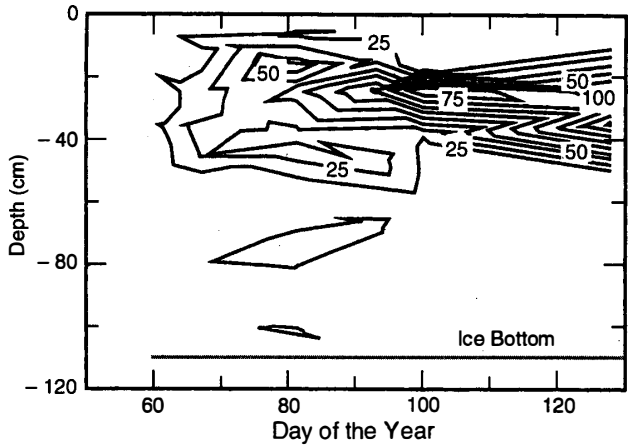


Fig. 10. Depth-time profiles of chlorophyll a concentration (μg l^{-1}) at site B between days 60 and 128. The increase at mid levels nearly coincides with the location of the refrozen porous layer at this site.

surface sea water values, evidence that the waters in the porous layer were replaced by sea water from below, that was relatively enriched in nutrients. Otherwise the nutrient increase could only be at most a few percent (from brine rejected from above by freezing) rather than the five to ten-fold increases shown in Fig. 9.

Chlorophyll *a* profiles of cores taken before and after the freezing period (Fig. 10) show that an algal bloom occurred in the region of the porous slush layer, where the interstitial water was apparently being actively exchanged with the underlying sea water. Figure 11 shows the integrated chlorophyll *a* from the cores at site B and shows the buildup in standing crop, with the buildup period concentrated during the porous layer freezeup (from day 60 to about day 80). As shown here, the variation in chlorophyll *a* determined from two to four cores in any given day was significantly less than the temporal change in average chlorophyll *a* during the buildup period.

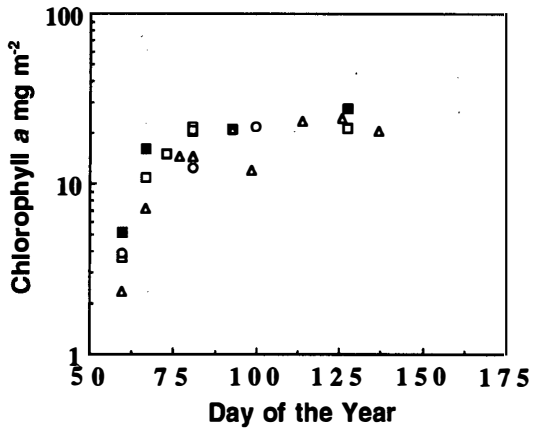


Fig. 11. Standing crop or depth-integrated chlorophyll a at site B as time series. Values steadily increased through the freezeup period of the porous layer at site B. (Symbols as in Fig. 6).

4. Discussion

The temperature-salinity and nutrient-chlorophyll *a* information provide two independent measurements that can be used to compute the amount of convective exchange. We therefore compare these two estimates of the exchange, called the Salt Flux Model and Nutrient Flux Model, respectively.

4.1. Salt flux model

We use a model which compares the salinities before and after the freezeup period and uses the experimentally determined temperatures to constrain how much the salinity of the fluid increased during the exchange period. This allows us to determine the rate at which fluid containing the extra salinity is removed from the porous layer. We have based this estimate on fluid rate on our field measurements, although the accumulated errors, from the initial and final salinity measurements, and from the temperature values, could change this value from that calculated here by $\pm 50\%$. From Figs. 4 and 8, the temperatures below the freezing front in either the porous (site B) or slush layer (site A) showed freezing points were constrained to salinities typically 1 to 2 psu greater (at 35 to 36 psu) than ocean salinity (34.1 psu). The layers started out with bulk salinities estimated at 16 to 18 psu as ice-water mixtures (50% each), and finished at sea ice averaging only 6 psu salinity. This salinity change was accomplished by drainage or expulsion of brine up to 2 psu greater, as constrained by the temperature, than inflowing brine salinity. Based on volumetric considerations, the total amount of brine flowing in and out is:

$$(S_i - \gamma S_f) V_t = V_o S_b - V_i S_{sw}. \quad (1)$$

Where S_i and S_f are the initial and final bulk salinities of the layer, V_t is the volume of the layer, V_i and V_o are the total volume flowing in and out of the layer and γ is the volume expansion of the layer (0.95). Where the estimated fraction (50%) that is water into ice. S_b is the salinity of the brine flowing out and S_{sw} is the sea water salinity. Because the ice expands as it freezes, the total volume flux out of the layer is slightly more than into the layer by

$$V_o = V_i + (1-\gamma)V_t. \tag{2}$$

Substituting and solving for V_i gives

$$V_i = \frac{V_t((S_i - \gamma S_f) - (1-\gamma)S_b)}{(S_b - S_{sw})}. \tag{3}$$

Using an original salinity of 17 psu, a final salinity of 6 psu, and $S_b - S_{sw}$ of 1–2 psu, a total of 0.7–1.4 m^3/m^2 and 0.9–1.8 m^3/m^2 of brine must be circulated during the freeze-up at site A and B, respectively. This is equivalent to replacing the liquid volume of the layers (0.1 to 0.17 m^3 brine) from 4 to 18 times.

4.2. Nutrient flux model

While the nutrient values shown in Fig. 9 from the porous layer are direct evidence of a sea water influx during the freezing period at site B, this information alone only indicates at least one exchange of water in the porous layer. However, examination of the fixing of nitrogen in the biological component, contained within the ice cores, can be used to estimate the total influx of nitrogen needed to sustain the biological production. With the values of nitrogen available from the surface sea water, we can then estimate whether more than one overturning occurred and provide a lower bound on the number of exchanges that possibly occurred.

Figures 6 and 11 show the changes in integrated standing crop at sites A and B. Using a nitrogen to chlorophyll *a* + phaeopigments ratio of 7.9 (std. dev. ±0.78) by a linear regression analysis (BANSE, 1977), we can convert the standing crop to an equivalent nitrogen content of 200 mg N m^{-2}. At both sites the primary algal growth was in the upper layers of the ice, in the slush and porous layers, as shown by vertical profiles of the concentration of chlorophyll *a* (Figs. 5 and 10). The increase in algal biomass at the depth of the maximum amount of pigment accumulation (site B) represented an increase of 73 mmol m^{-3} of algal nitrogen biomass. Since the initial brine contained less than 5% of the observed increase in biomass nitrogen (including ammonium), water exchanges must have occurred to bring it up to the level of the uptake. Surface sea water nitrate (Fig. 9) is also insufficient, in one exchange, to have sustained the increase, even at full utilization. For the standing crop observed, fluxes of seawater were estimated to exceed 0.015 m^3 m^{-2} day^{-1}, a minimum volume flux necessary to both sustain the algal population and increase the nutrients to their sea water value (scaled to salinity) as observed in the ice at the end of the three week period of algal growth (FRITSEN *et al.*, 1994). The original brine in the porous and slush layers occupied 0.1 to 0.2 m^3 (depending on the layer thickness and assumed ice content, 50%). Therefore the integrated flux of sea water exceeded the volume of the liquid portion of the layer, over 20 days, by 1.5 to 3 times, or the liquid volume in the layer overturned 1.5 to 3 times. These values are a lower bound on the number of overturnings, since it assumes all of the nitrogen available is fixed in the algal growth plus one "recharge" to the observed seawater nutrient values, which were present at the end of the freezeup period. In reality, only a portion of the nutrients available in each overturning are utilized in algal

production, so this estimate of the number of layer overturnings is a minimum in this approach. (For example, if only half the nutrients in each overturning are fixed biologically, then the estimate of the number of overturnings by this approach would be doubled to 3 to 6).

5. Conclusions

Two Antarctic sea ice biological systems, a surface slush and a near-surface porous layer community, were measured in time series during the fall freeze-up period. We observed the development of algal blooms in both these locations in the autumn period. The initiation of freezing drives convective overturning that provides the nutrients from underice sea water for the algal community to develop. Independent estimates of the number of overturnings and rates of fluid exchange within the ice, from temperature-salt flux and chlorophyll a-nutrient flux estimates yielded similar values, indicating the fluid within the ice exchanged with the sea water below the ice between about 2 and 18 times during the three-week fall freeze-up period of these initally partially frozen layers. The layers were underlain by ice with cm-sized channels that allowed the fluid flow to occur relatively freely. The level of biological production seen in these near-surface layers (1760 mg C m^{-2} and 200 mg N m^{-2}) require substantially more nutrients than available from the initial volume of fluid within the layers. We can conclude that these high levels of production are necessarily driven by a number of sea water exchanges to provide sufficient nutrients to support the observed algal bloom. Since surface and internal colored bands of algae are observed frequently within the Antarctic sea ice, we further conclude that the convective overturning is also a frequent occurrence within the Antarctic pack ice at other locations.

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