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# Algae concentrated by frazil ice: evidence from laboratory experiments and field measurements

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**Abstract:** A number of studies have suggested that high concentrations of organisms in sea ice may be the result of harvesting and concentration by frazil ice. Laboratory experiments have shown that frazil ice can concentrate organisms from two to four times above levels in the underlying water. The concentrations in nature, however, can be considerably higher. The apparent discrepancy between laboratory results and field observations can be explained by the longer temporal and spatial scales that allow more contact of ice crystals with particles and with one another in the sea. It is also likely that small-scale circulation features, such as Langmuir circulation, enhance the ability of frazil ice to concentrate organisms in a natural setting.

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## Introduction

A number of studies have reported that organisms ranging from microalgae to foraminifera may be harvested from the water column and concentrated in newly-forming sea ice (e.g. Bunt 1968, Bunt & Lee 1970, Lipps & Krebs 1974, Garrison *et al.* 1983, Spindler & Dieckmann 1986, Ackley *et al.* 1987, Watanabe & Satoh 1987, Dieckmann *et al.* 1986*a*, *b*, 1988). One mechanism proposed to explain high concentrations of organisms in young ice is that frazil ice crystals both form on suspended particles and that particles encounter and adhere to frazil ice crystals as they form and rise to the sea surface (Ackley 1982, Garrison *et al.* 1983). Although the process of frazil ice formation has been studied in the laboratory (e.g., see Martin 1981), the question of how organisms are incorporated has received little attention. Population comparisons from field samples (Garrison *et al.* 1983) have already indicated that no size selection occurs when organisms are incorporated into frazil ice from the water column. We have now examined the ability of frazil ice to harvest organisms in the laboratory and have related these results to measurements of algal concentration in samples of new and young ice from the Antarctic pack ice.

## Methods

*Laboratory experiments*

Laboratory experiments were designed to determine if frazil ice crystals could harvest and concentrate suspended algal cells. Frazil ice was produced in a Plexiglas column with an aluminum base plate to promote ice formation at the bottom of the column (Fig. 1). Frazil ice crystals formed at the base of the chamber were able to rise through approximately 1.9 m of sea-water before they accumulated at the top of the chamber.

Experimental runs consisted of suspending algal cells in the sea-water column, measuring the concentration of chlorophyll *a* before the start of ice formation, allowing frazil ice to form and surface slush ice to accumulate, and then to measure the concentrations of chlorophyll *a* in ice and sea-water at the end of the experiment. A stirring motor in the base of the chamber was used to produce and maintain a homogeneous distribution of sea-water and suspended particles until ice formation was initiated. An initial chlorophyll sample was collected by siphon from mid-column before the beginning of ice formation. Frazil ice generated at the base of the column rose to the surface until 500–1200 ml of slush ice had accumulated at the surface. The surface slush ice was retained and analysed for chlorophyll concentration. After all ice was removed from the chamber, a second sample was drawn from the algal suspension remaining in the chamber. Ice samples were allowed to melt in the dark and both ice and water samples were then filtered onto GF/F glass fibre filters, and chlorophyll *a* was extracted with 90% acetone. Chlorophyll *a* concentrations were measured by standard fluorometric methods (Parsons *et al.* 1984). Generally, three replicate samples each of pre-freeze water, post-freeze water and frazil ice were collected and analysed. There were two variations in our measurements of chlorophyll *a* in frazil ice. In the first three of seven experiments, the total chlorophyll in the surface slush ice was measured. In the latter experiments, the slush was collected and interstitial water allowed to drain through a strainer. Chlorophyll *a* levels were then determined for both the remaining ice and the interstitial or 'drain' water. All experiments were conducted in a –20°C cold room.

The algal cultures used in the experiments were diatoms

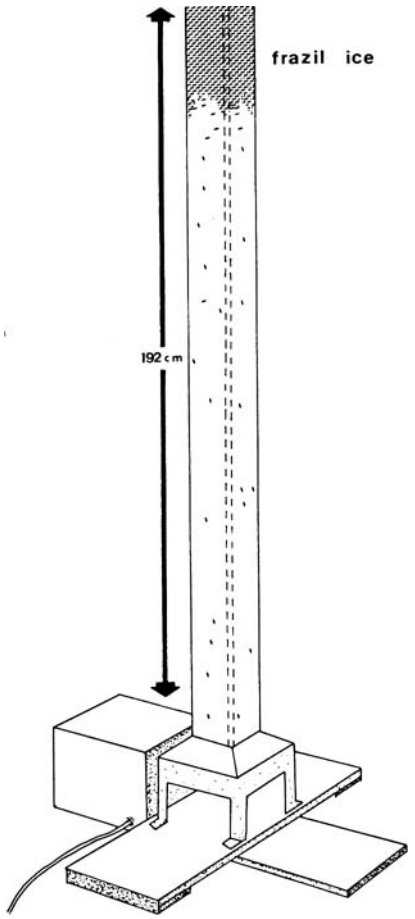


**Fig. 1.** Diagram of frazil ice generating chamber. (Dimensions = 10.8 × 10.95 × 192.5 cm; volume *c.* 25 litres.)

(primarily *Nitzschia* sp. and *Chaetoceros neogracile* Van Landingham) isolated from Antarctic pack ice and maintained in rough cultures at U.C. Santa Cruz. For experimental work, cultures were grown to high densities in 2.7 litre flasks. These were transported on ice to the laboratory at the U.S. Geological Survey on the day of the experimental runs where they were diluted with enough cold, filtered sea-water to fill the experimental chamber.

*Field samples*

We have sampled sea ice in several stages of ice formation and growth as part of our field studies in 1980, 1985, 1986, 1987, and 1988. Chlorophyll *a* was measured in both ice and in the water column and thickness and other characteristics of the ice were also recorded as part of our studies.

## Results

In all of our laboratory experiments the concentration of algae in the surface slush ice was higher than in the initial suspension in the water (Fig. 2a–g). In two of the experiments, however, there was considerable variability among the replicate chlorophyll *a* measurements, so that the mean concentrations were not significantly higher (Fig. 2d, g). The concentration factors (chlorophyll *a* in ice/water) averaged 1.8 ± 0.9 with a maximum of *c.* 4. Although the concentrations of chlorophyll in the experiments were higher than would be found in natural conditions, there was no indication that concentration factors were related to concentration of initial suspension, the organisms used, the duration of the experimental run, or to the amount of frazil ice formed. The absolute concentrations of chlorophyll retained by ice were a linear function of pre-freeze concentrations normalized by volume of ice formed (Pearson correlation $r = 0.997$, $n = 7$), suggesting that the algal cells harvested were a function of the encounters between ice crystals and cells.

In field samples a considerable amount of variability in chlorophyll *a* was found among the various types of new and young sea ice (Fig. 3a). Many of these measurements represent concentration factors which agree with the *c.* 2–4 fold concentrations produced in the laboratory experiments (Fig. 3b). However, other samples ranged up to over 80 times the concentration of the underlying water column.

## Discussion

In all of the laboratory experiments frazil ice showed an ability to harvest and concentrate algal cells from the underlying water, thus, the ability for frazil ice to trap algal cells has been adequately demonstrated. The higher chlorophyll *a* concentration in the 'drain' water as compared to that retained by ice crystals, suggests that the mechanism is a simple trapping (or filtration), but nucleation cannot be entirely ruled out as a concentrating factor in these experiments.

The concentration factors of chlorophyll *a* in natural samples were often considerably higher than we were able to produce in the laboratory. The >5 to >10 times higher concentration found in grease ice and very young pancake ice is convincing evidence that physical concentration takes place in nature (Fig. 3 and Garrison *et al.* 1983). There are, however, differences in ice formation in the field and in the laboratory that account for the apparent discrepancy. In the laboratory, the contact between suspended cells and rising ice crystals is limited to the < 2 m path of the rising frazil ice crystals over the few minutes required for them to reach the surface. The depth at which frazil ice forms in the deep water pack ice regions is not known. Thermohaline convection, which Weeks & Ackley (1982) propose as one mechanism for generating frazil ice at sea, can extend to tens of metres (Foster & Weiss in press, T.D. Foster, personal communication 1989, also see Dieckmann *et al.* 1986*a*). In the field, we have also observed horizontal drift of several metres as frazil ice forms and aggregates at the surface. Moreover, during the duration of the laboratory experiment

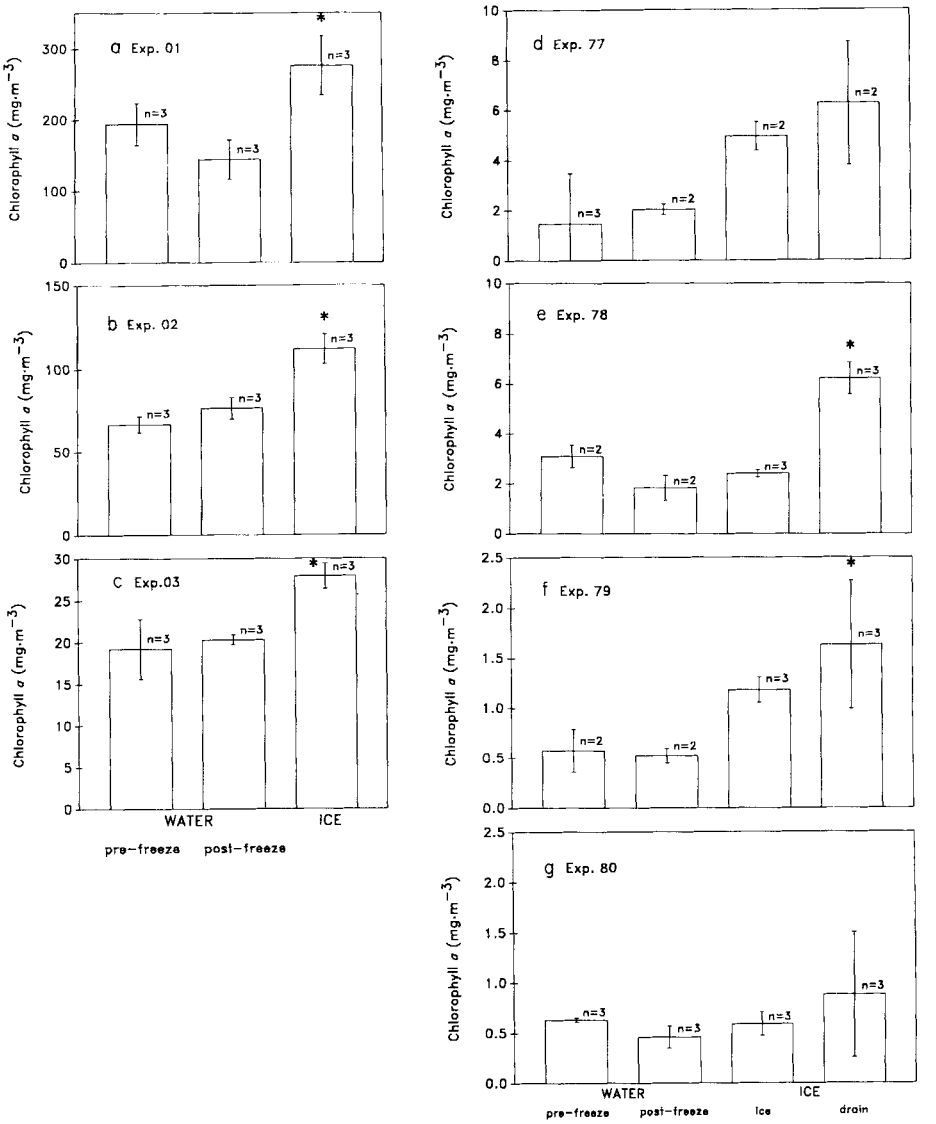


**Fig. 2.** Histograms showing results of laboratory experimental runs. Mean chlorophyll *a* concentrations and standard deviations for n replicates are shown for each histogram bar. Pre-freeze refers to samples before frazil ice formation, and post-freeze refers to samples at end of experimental run. * signifies that the concentrations used were significantly different from pre-freeze water concentrations (Duncan multiple-range test, $\alpha = 0.05$). In experiments 77–80, the slush ice was separated into ice crystals and interstitial (drain) water.

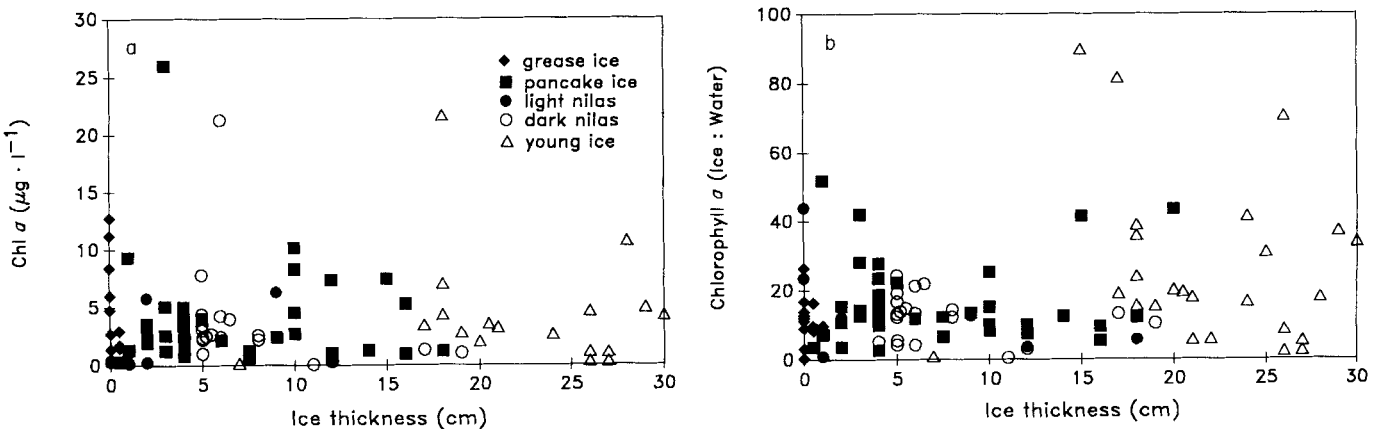


**Fig. 3.** Chlorophyll *a* in newly forming and young sea ice as a function of ice type and thickness. **a.** Absolute concentrations. **b.** Concentration factor expressed as a ratio of chloropyll *a* in the underlying water. Ice classifications are those recommended by Stringer *et al.* 1984.

(usually about 30 minutes), there is limited time for contact between ice crystals so that flocculation, which occurs in nature (see Martin 1981), is less likely to occur. It seems likely that both increased encounters between suspended cells and frazil ice crystals and increased filtration (or harvesting) efficiency of flocculated frazil ice result in higher concentrations factors in nature, but it would be impractical to scale up the experimental apparatus to test this directly.

There may be secondary mechanisms which operate in conjunction with frazil ice harvesting to produce the concentrations of organisms found in ice in nature. Langmuir circulation (e.g., Bainbridge 1957, Stavn 1971) is a likely mechanism. Langmuir circulation clearly aggregates frazil ice in converging circulation cells (see fig. 5 in Martin 1981), and this surface aggregation of frazil ice crystals should act as a filter for suspended organisms transported in these circulation cells. The scale of the Langmuir circulation is sufficient to produce most of the concentration that we observed in nature. For example, we calculated that the concentration factors observed in the field could be explained by harvesting cells from one to two metres depth. In the extreme concentration, the harvesting would still be less than 6 m. Since high concentrations in ice versus low concentrations in the water column are likely to be found after harvesting, this calculation is a conservative estimate of the depth of harvesting.

Ackley *et al.* (1987) and Shen & Ackermann (1988) have suggested another possible mechanism which requires a wave field propagating through a layer of surface frazil ice to concentrate suspended material in ice. This model has not yet been extensively evaluated with experimental evidence or with field observations.

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