

BEAUFORT SEA PLANKTON STUDIES: WINTER-SPRING  
STUDIES IN STEFANSSON SOUND AND OFF NARWHAL ISLAND  
NOVEMBER 1978-JUNE 1980

by

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I. Summary of objectives, conclusions, and implications with respect to OCS oil and gas development.

A. Objectives

Our objectives were to 1) determine the relative contribution of the ice algae, phytoplankton, and benthic microalgae to primary production in the Beaufort Sea coastal zone during the winter-spring period of ice cover; 2) determine the species composition of these communities and the degree of linkage or interaction between them; 3) follow the development of the spring ice algal bloom and determine the environmental factors controlling the timing, distribution, and magnitude of this bloom; and 4) assess the winter density distribution and environmental requirements of zooplankton, phytoplankton, and ichthyoplankton in the nearshore Beaufort Sea.

B. Conclusions

1. Ice algae were responsible for nearly all primary production during the winter-spring period, with only minimal contribution from the phytoplankton and benthic microalgae. The bulk of this production took place from April to June and amounted to ca.  $0.7 \text{ g Cm}^{-2}$ . In addition, an unknown amount of primary production probably occurred in the ice during the fall of 1980. The only published reference to a fall bloom in the ice of the Beaufort Sea is that of Hsiao (1980). Although higher rates of production take place in the water column and perhaps the benthos during the open water period, ice algae are the prime source of carbon during ca. 30% of the period in which primary production may occur.

2. The ice algal community was composed primarily of pennate diatom species typical of the under-ice community in other arctic areas. These same species dominated the phytoplankton in early spring, but cells were **unhealthy** and appear to have originated in the ice, being only temporary members of the **phytoplankton**. Small **microflagellates**,  $< 6 \mu\text{m}$  in diameter, were abundant in both the ice and water column, but they do not appear to be photosynthetic, and their importance as a food source is not known, although some copepod species apparently prefer them. Some ice algal species occurred in the benthic **microalgal** community, but most of these species were represented by dead or moribund cells and may be considered **detrital**. The benthic **microalgal** community formed a separate assemblage, with high standing stocks that lay dormant during the winter period, but are known to be important primary producers during the summer.

3. Light appears to be the major environmental factor controlling primary production during this period. The ice algal bloom is initiated by increasing solar radiation in spring and the distribution and magnitude of the bloom is determined largely by ice turbidity and snow cover which limit light transmission through the ice. Production in the water column and benthos in early spring is inhibited by shading from the ice algal layer when it is present.

4. Ice algae provide a rich food source for animals, such as protozoans, copepods, nematodes, and amphipods that live in direct

association with the underside of the ice. Ice algae are also a major source of living and **detrital** material for animals living in the water column and **benthos**.

5. Although data given here do not indicate it because we did not sample the spring **phytoplankton** bloom, there is a definite species difference between the ice algal bloom and the **phytoplankton** bloom in the water column, with pennate diatoms dominating the ice community and **centric** diatoms dominating the **phytoplankton** (water column) community. There is **also** a time lag with the ice algae occurring in April-June and the **phyto-**plankton occurring during and after breakup when sufficient light reaches the water column.

6. Copepods are the most abundant zooplankton both in terms of number of animals and species and are present throughout the **winter-**spring period. All life cycle stages are present. Some species apparently prefer **microflagellates** that are present all winter as a food source, Other important components of the nearshore zooplankton community are amphipods and mysids, but they were never caught in large numbers, perhaps because of **our** collecting methods. Hydrozoans became abundant in spring.

### C. Implications

The ice algal community occurs as a layer only a few centimeters thick on the under surface of the ice in spring and would be directly susceptible if an oil spill came in contact with the ice. The **oil** could damage or destroy the ice **algae** by direct toxic effects, by limiting exchange with the underlying seawater, or by reducing light levels. Oil-related activity prior to the development of the bloom could affect ice algal production by increasing ice turbidity from oil or suspended sediments in the ice that would reduce light transmission through the ice and thus **limit algal** growth.

There are no other sources of primary production during the early spring, therefore, animals present that depend on primary production for their food supply and spend a significant or critical portion of their life cycles associated with the ice would be seriously affected. This could have serious implications farther up the food chain for fishes, birds, and mammals that depend on these invertebrates for their food.

**Phytoplankton** and benthic **microalgae**, while not present **in** large numbers during the spring, would be affected by direct toxic effects and reduced **light** levels. These factors could, perhaps, destroy or severely **impair** seed stock that normally produce the **spring phytoplankton** bloom and the summer **benthic microalgal** populations.

The effects of an oil spill could be quite local, but could also spread over a wide area depending on environmental conditions. A spill in the fall could affect primary productivity of a whole season by damaging ice algal seed stocks. Whether early and timely cleanup would reverse this affect is not known, nor is it known what affects residual pollutants may have on the **microalgal** populations in the ice, water column, or **benthos**. Relatively rapid generation times of **microalgae** and some zooplankton would alleviate the effects of an oil spill in a short period of **time** in temperate regions,

but generation times for most **microalgal** species found in the Arctic are not known, and some important zooplankton species are known to take at least two years to ~~complete~~ their life cycles.

## II. Introduction

### A. General nature and scope of the study

The sources of primary productivity and carbon pathways that support the ecosystem of the nearshore Beaufort Sea are poorly understood. In particular, there is a gap in our knowledge of the system during the winter-spring period of ice cover, which accounts for the majority of the annual cycle.

One of the major components of the nearshore ecosystem that has not been intensively studied is the algal community living in and on the underside of sea ice, along with those organisms that are sometimes associated with it such as amphipods and perhaps fish. It is not known how important the ice algae are as a food source in the nearshore area, but their presence about two months before the **phytoplankton** bloom in the water column" must lengthen the growing season for those animals that are able to utilize them.

In addition, benthic **microalgae** have been shown to account for a significant amount of the total productivity of some nearshore ecosystems, including the nearshore Chukchi Sea near Barrow, Alaska (Matheke and Homer 1974). Its importance in the nearshore Beaufort Sea ecosystem is not known.

Our objective was to assess the winter density distribution and environmental requirements of zooplankton and **phytoplankton** in the nearshore Beaufort Sea, and to undertake an integrated study of ice algae, water column, and **benthic microalgae** production to provide comparisons among these habitats and allow us to assess the relative importance of these communities during the critical spring growing season. Cooperative studies with RU's 6 and 537 were designed to provide information on the benthic invertebrate community and its utilization of the ice algae and **benthic microalgae**, help determine the degree of linkage between the ice algae and **benthic microalgal** communities, determine the areal extent and patchiness of the ice algae, and the carbon pathways in the system, thus providing a relatively complete study of the winter-spring ecosystem.

### B. Specific objectives

1. Determine the primary productivity, standing stocks (plant pigments and cell numbers), and species composition of the ice algal, **phytoplankton**, and **benthic microalgal** communities in the Stefansson Sound area.

2. Assess the relative importance of these communities.

3. Follow the development and decay of the spring ice algal bloom.

4. Determine the species composition and abundance of the zooplankton community.

5. Measure environmental parameters, such as light, temperature, salinity, nutrient concentrations, and snow cover, that may affect these communities.

6. Complete and submit a final summary report on winter-spring studies.

C. Relevance to problems of petroleum development

As oil development is planned for the nearshore waters of the Beaufort Sea, and exploration drilling is likely to occur primarily in winter, it is important to assess the biological importance of the area and to determine the ecosystem's vulnerability to oil-related activities during the ice covered months of the year.

Microalgae associated with the underside of the ice appear to be responsible for the bulk of the primary production that supports the nearshore ecosystem during the period. An understanding of the dynamics of this community, and the fauna closely associated with it, is important in assessing periods that may be particularly sensitive to the effects of oil-related activity. In addition, a better understanding of the relative roles of the ice algae, water column, and benthic communities is important in predicting the probable effects of an oil spill on the nearshore ecosystem during the winter-spring period.

D. Acknowledgements

Winter sampling in Nov 1978, Feb and Mar 1979 was done by Tom Kaperak, who also identified the non-copepod zooplankton. Gayle Heron identified the copepods. May 1979 sampling was done by diver Jim Hanes and Rita Homer, who also analyzed the plant pigment and standing stock samples from all the Stefansson Sound samples. Kendra Daly collected the one zooplankton sample from May 1979.

Gary F. Smith, Coastal Environmental, Bellingham, WA., redesigned and fabricated the ice sampler-incubation chambers and provided the divers, Ron Poirot and Jim Dougherty, for the Apr-Jun 1980 sampling period. Carl Schrader and Dave Murphy spent 2.5 mo at Prudhoe Bay doing the field sampling and then analyzed the samples in Seattle. Ron Atlas and Paul Hill analyzed the benthic microalgae productivity samples; Gayle Heron identified the copepods. Kate Persons and Steve Petersen provided logistic support at Prudhoe Bay. Personnel from RU 6 also helped in the field. NOAA helicopter pilots and mechanics provided transportation and logistic support, and, for several weeks until we got adequate stoves, provided heaters for the field site.

### III. Current state of knowledge

#### A. Biota

In the nearshore Beaufort Sea area, early reports from the Canadian Arctic Expedition in 1913-1918 were primarily taxonomic studies (Bigelow 1920; Shoemaker 1920; Willey 1920; Schmitt 1919; Mann 1925). Plankton studies in the nearshore area before the late 1960's were limited. Now, information concerning the plankton of this area is gradually accumulating, primarily as a response to increasing oil and gas exploration and development.

In the Harrison Bay-Simpson Lagoon region, Alexander (1974) found the highest primary productivity rates occurred in deeper, more saline water, with maximum productivity occurring in August. Annual productivity in the water column was estimated to be more than 10-15 g C m<sup>-2</sup>. Nutrient-rich water from the Colville River may, at least in part, be a major factor contributing to the relatively high productivity rates. Species composition of the phytoplankton community varied with depth, season, and year, but many cells were small, in the nanoplankton range. Ice algae, benthic microalgae, and zooplankton were not studied in this area.

Horner *et al.* (1974) described the plankton of Prudhoe Bay in terms of primary productivity, standing stock, species composition, and spatial variability, along with hydrographic conditions. High concentrations of chlorophyll a and pennate diatoms were present in the bottom layer of ice in May and June, but no primary productivity measurements were made. However, annual primary productivity of the ice algal community in Prudhoe Bay was estimated to be ea. 1 g C m<sup>-2</sup>.

During the open-water season, three phytoplankton communities were present with pennate diatoms predominating in Prudhoe Bay immediately after breakup; centric diatoms dominating in deeper, more saline water outside the bay; and flagellates dominating in brackish surface water. Productivity was highest in the diatom-dominated communities. Annual primary productivity in the water column inside Prudhoe Bay was calculated to be ea. 9 g C m<sup>-2</sup> and that in the lagoon system to be ca. 18 g C m<sup>-2</sup>. Nutrient concentrations were higher in winter and early spring, with nitrate being rapidly utilized during spring and probably limiting growth in summer. Benthic microalgae were not studied.

Three zooplankton communities were also found, with copepods being numerically dominant in all. Inside Prudhoe Bay, *Acartia clausi* was the most abundant species and meroplanktonic larvae were absent. In the lagoon system, *Calanus glacialis* and *Pseudocalanus minutus* were dominant; small numbers of meroplanktonic larvae occurred near Reindeer Island. Outside the Midway Islands, meroplanktonic larvae became important with decapod, polychaete, and barnacle larvae all present.

The only previous study to compare production of the ice algal, phytoplankton, and benthic communities was done in the nearshore Chukchi Sea at Barrow, Alaska, (Clasby *et al.* 1973; Matheke 1973; Matheke and Homer 1974; Alexander *et al.* 1974). This was also the first study to look at standing

stocks (chlorophyll *a* and cell numbers) and primary productivity for all three communities at the same time. In this study, sampling started in Jan-Feb and continued until late Aug in two successive years. Only the period of ice breakup was not covered. *In situ* techniques were devised to measure productivity of the ice (Clasby *et al.* 1973) and benthic (Matheke 1973) microalgal communities so that cells would not be physiologically stressed by being brought from relatively high temperature, low light conditions under the ice to low temperature, high light conditions at the surface. The Barrow studies showed that the ice algal community developed in response to a critical light level in early April; maximum production occurred in late May with a rapid decline in early June as the ice decayed. Production in the water column was low until after the ice algae disappeared and breakup began. Benthic microalgal production was low while ice cover was present with motile, solitary pennate diatoms being the most abundant organisms. After ice breakup, a mat of *Amphipleura rutilans* (Trent.) Cleve developed and was still present when sampling ended in August. The benthic microalgae became the most important source of primary productivity after ice breakup, being eight times that of the ice algae and two times that of the phytoplankton (Matheke and Homer 1974).

The early literature on ice algae has been reviewed extensively (Alexander *et al.* 1974; Homer and Alexander 1972; Homer 1976, 1977; Alexander 1980).

As part of the OCSEAP project, RU 536 collected epibenthic and planktonic invertebrates from many stations in the nearshore Beaufort Sea (Broad *et al.* 1979). *Mysis litoralis* and a number of amphipod species that have also been collected in plankton samples were the most abundant species found in epibenthic sled tows.

LGL (RU 467) found that invertebrates were important in the Simpson Lagoon area if they provided food for fish and birds, Most of the feeding occurred in shallow lagoons and bays in summer and plenty of invertebrates were available for food. LGL also found that primary production by diatoms in summer was the major source of carbon for the system, with ice algae being a secondary source; benthic microalgae were thought to play a small role in the food web (LGL 1981).

Schell (1980a) estimated ice algae annual productivity in Simpson Lagoon, Stefansson Sound, and offshore based on daily productivity measurements (measured in Stefansson Sound by RU 359), literature values, and observed increases in standing stocks, and compared these estimates with values obtained by <sup>14</sup>C uptake experiments in other Alaskan areas. He calculated low productivity within Simpson Lagoon,  $0.178 \pm 0.166 \text{ g C m}^{-2}$ ; higher rates in Stefansson Sound,  $1.43 \pm 1.13 \text{ g C m}^{-2}$ ; and highest rates,  $1.69 \pm 0.89 \text{ g C m}^{-2}$ , offshore.

Farther east in the southern (Canadian) Beaufort Sea, Hsiao *et al.* (1977) found that standing stock in the euphotic zone decreased with increasing distance from shore and the Mackenzie River delta. Diatoms were more abundant near shore, in river mouths, and in surface water at ice stations, while flagellates were more common offshore. Phytoplankton was more abundant above 5 m than in deeper water. Primary productivity

was also found to decrease with increasing distance from shore and the river mouths, primarily because of higher nutrient concentrations and warmer temperatures in the coastal waters. From Hsiao *et al.*'s (1977) hourly productivity data and assumptions previously used by RU 359 (English and Homer 1977) annual productivity in this area was calculated to be ea.  $3 \text{ g Cm}^{-2}$ .

Hsiao (1980) identified 196 species of **microalgae** from annual shore-fast ice in the Canadian Arctic, including the Eskimo Lakes region of the southern Beaufort Sea, Eclipse Sound in the high Arctic; and Frobisher Bay in the eastern Arctic. The ice algal **communities** developed slowly from **late** fall through winter, increasing exponentially in early spring, reaching a peak just before the thaw period, and declining rapidly as the ice melted. Standing stock was greatest at the bottom of the ice and pennate diatoms were the most abundant organisms.

Dunbar and Acreman (1980) presented data on standing stocks and species composition of diatoms in sea ice from Robeson Channel and Barrow Strait in the high Arctic, Hudson Bay, and the Gulf of St. Lawrence. Nutrient concentrations in all areas were similar, but chlorophyll *a* was one to two orders of magnitude higher in the northern areas than in the Gulf of St. Lawrence. In *the* northern areas, pennate diatoms comprised 96-99% of the population, while in the Gulf of St. Lawrence, pennate diatoms comprised 57% of the population with the remainder being **planktonic centric species**.

## B. Nutrients

Inorganic nutrient levels in the surface waters of the Beaufort Sea undergo marked seasonal fluctuations. During the summer, nitrate and phosphate drop to very low or undetectable levels, and the system is considered to be strongly nitrogen limited. This results from high **phytoplankton** utilization and limited vertical mixing due to high water column stability which develops in response to ice melt and increased insolation (Hufford *et al.* 1974; Aagaard 1977). In the winter when stratification breaks down, nutrient concentrations increase to relatively high levels as a result of increased vertical mixing and regeneration at a time when plant utilization is low.

Schell (1974) has documented the regeneration of nitrogenous nutrients beneath the winter ice cover in shallow, nearshore and estuarine areas. This suggests the possibility that a substantial fraction of the nitrate in arctic coastal waters may be regenerated *insitu* during the winter months rather than deriving from offshore deep-water sources. It is suspected, however, that much of the nutrients regenerated in coastal waters may be transported offshore by **thermohaline** convective processes during **winter (Nov-Mar)** (Schell pers. comm.).

Winter nutrient levels near Point Barrow have been reported to range up to  $1.7 \mu\text{g-at l}^{-1}$  phosphate,  $9.2 \mu\text{g-at l}^{-1}$  nitrate plus nitrite, and  $35 \mu\text{g-at l}^{-1}$  silicate (Matheke 1973). Similar values have been reported by Homer *et al.* (1974) for Stefansson Sound. The same authors reported summer levels ranging from 0-0.9  $\mu\text{g-at l}^{-1}$  phosphate, 0-2.7  $\mu\text{g-at l}^{-1}$

nitrate and 5-28  $\mu\text{g-at } \ell^{-1}$  silicate.

Upwelling has been documented by Hufford (1974a) along the eastern portion of the shelf and may be a major source of nutrients to the euphotic zone in this region. As a result of local easterly winds, nutrient-rich water from 100-200 m depth is upwelled and advected westward over the mid-portion of the shelf. Observed as far east as Barter Island (144°W), upwelling is largely limited by the amount of open water on which the wind may act. The rather persistent ice cover in the western shelf area may be responsible for the lack of observed upwelling in that region.

Strong onshore-offshore nutrient gradients are often apparent during the summer, due largely to the influence of river runoff, Hufford (1974b) found that in the area between Point Barrow and Barter Island, nitrates decreased from 1.5  $\mu\text{g-at } \ell^{-1}$  nearshore to very low or undetectable levels near the shelf break. At the same time, he found that river discharge in the area contained 3-15 times the amount of nitrates found in the coastal surface layer. Silicates followed a similar pattern decreasing from 10  $\mu\text{g-at } \ell^{-1}$  near the mouth of the Colville River, to less than 2  $\mu\text{g-at } \ell^{-1}$  100 km offshore. Phosphates deviated strongly from this pattern, being low or not detectable nearshore and increasing to 0.8  $\mu\text{g-at } \ell^{-1}$  near the shelf break. This pattern reflects the high input of nitrates and silicates by river water and the relative lack of phosphates (Codispoti and Richards 1968; Grainger 1974). River flow is seasonal, however, and the majority of nutrient input from rivers occurs during spring breakup, as has been documented by Hamilton *et al.* (1974) for the Colville River.

In the Canadian Arctic, the Mackenzie River has a substantial impact on the southern Beaufort Sea. Approximately half of the freshwater runoff to the Beaufort Sea flows through this river. The plume generally flows eastward along the coast and is deflected north and westward near Amundsen Gulf to mix with waters of the Beaufort Gyre (O'Rourke 1974). Grainger (1974) found the highest surface nutrients immediately off the river mouths, with concentrations decreasing seaward. With the exception of silicate, nutrients were much higher in the surrounding sea where the river discharges than in the river proper. These high nutrient concentrations may be largely attributed to the estuarine circulation typical of many large rivers (Redfield *et al.* 1963). In this type of circulation, a sub-surface counter-current forms to replace water entrained in the surface flow causing nutrient concentrations to increase upstream relative to the motion of the surface layer. In addition, microbial activity was found by Griffiths *et al.* (1978) to be very high in the plumes of major rivers and nearshore sediments of the North Slope. Decomposition of river-borne detritus must be a major source of nutrients to the nearshore environment.

#### IV. Study area

Two areas were sampled (Fig. 1). In Nov 1978, and Feb, Mar, and May 1979, samples were collected in Stefansson Sound near RU 356's dive site 11 (70°19'N, 147°34.4'W) in the boulder patch area. From Apr-Jun 1980, a site was established on a large, flat pan in the shorefast ice ca. 300 m seaward of Narwhal Island (70°24.0'N, 147°31.1'W). The Narwhal

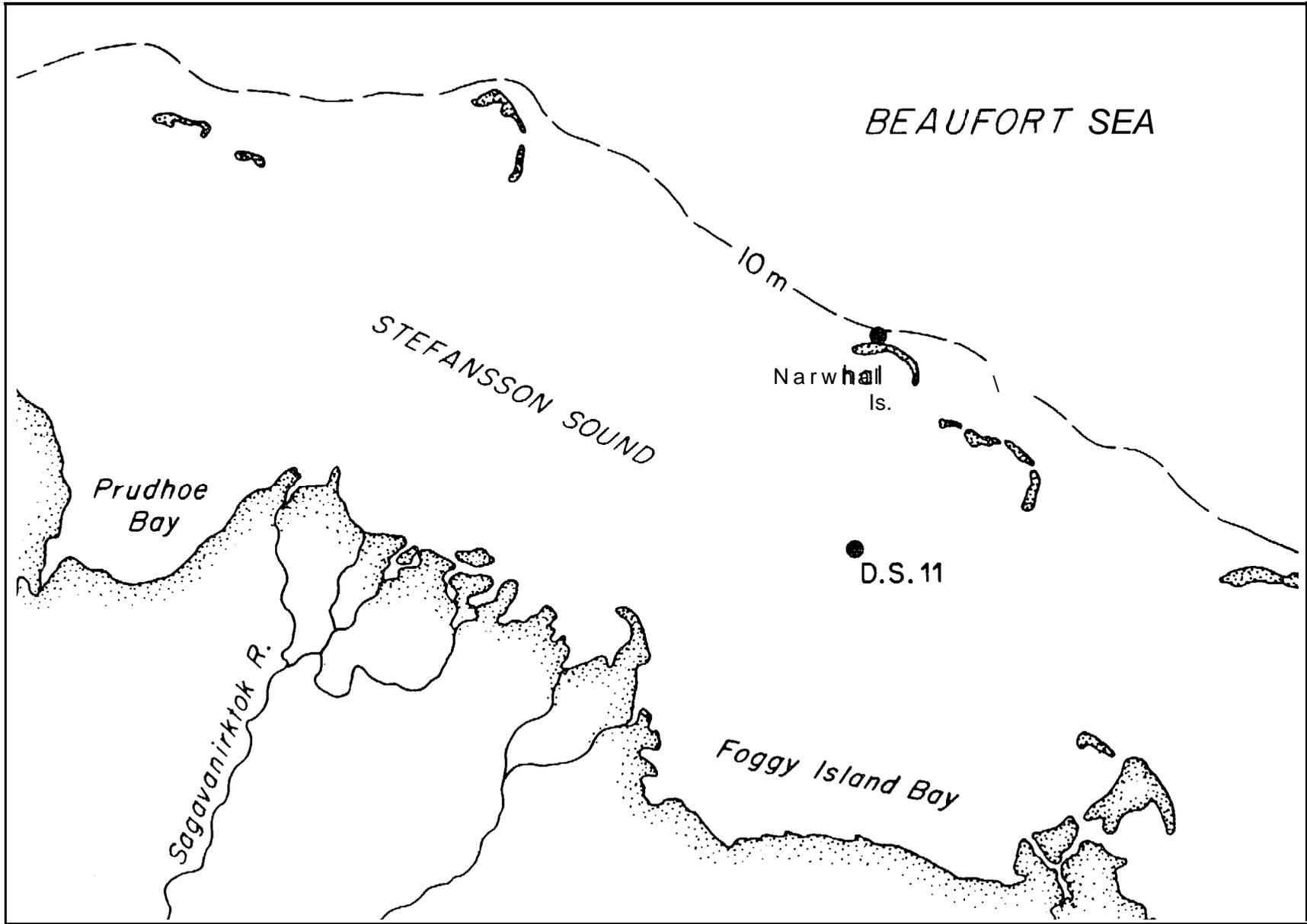


Fig. 1. Location of study sites in Stefansson Sound (1978-1979) and off Narwhal Island (spring 1980).

Island station was occupied jointly with RU 6 (Fig. 2).

## V. Sources, methods, and rationale of data collection

### A. Sources and rationale

Winter and spring samples were collected in Nov 1978 and Feb, Mar, and May 1979. In order to provide more detailed coverage of the dynamic spring period, a station was occupied at approximately twice weekly intervals from early Apr through mid-Jun 1980. This provided the opportunity to follow the cycle of the ice algal community from its beginning until its disappearance at the end of the bloom, as well as the early development of the spring phytoplankton bloom in the water column and the benthic microalgal bloom.

Sampling during the 1978-79 period was done in the boulder patch area of Stefansson Sound near dive site 11 established by RU 356. This area was selected because of the ability to share logistics support and data with other RU's (6, 356, 537).

In spring 1980, we planned to continue sampling in this area and to add a station outside the barrier islands in an area more typical of the whole lease area that would allow a comparison between the two areas. However, a series of ice cores collected in early April with a SIPRE corer indicated the presence of a layer or layers of sediment in the ice throughout the lagoon system. The sediment layers effectively reduce the amount of light reaching the bottom of the ice where the ice algae are, thus inhibiting their growth. No traces of ice algae were seen on the bottom of the lagoon ice. Relatively clear ice with traces of ice algae were found just seaward of Narwhal Island and we decided to concentrate our efforts at that site. We returned to the boulder patch area once during the study to measure chlorophyll  $a$  levels in the bottom ice.

We have chosen to separate the presentation of the methods by date and kind of sample collected because sampling methods varied to some extent depending on equipment available and logistics support. In the results and discussion sections, we have chosen to separate the data by sampling location, Stefansson Sound (1978, 1979) and Narwhal Island (1980).

We have studied four distinct communities. The ice algal community consists of diatoms, dinoflagellates, flagellates, and associated invertebrates and sometimes fish that live in the interstitial water between ice crystals. This community, often called the epontic community (Bunt and Wood 1963), occurs on the bottom of sea ice in spring, Mar-Apr to mid-Jun. It is not present in the nearshore area in summer. This community has also been referred to as an upside down benthic community (Mohr 1959).

The phytoplankton community consists of diatoms, dinoflagellates, and flagellates that live in the water column. This community is present in abundance in late spring (breakup) and during the summer. The spring bloom probably occurs during ice breakup, but no data are available from the lease area to support this.

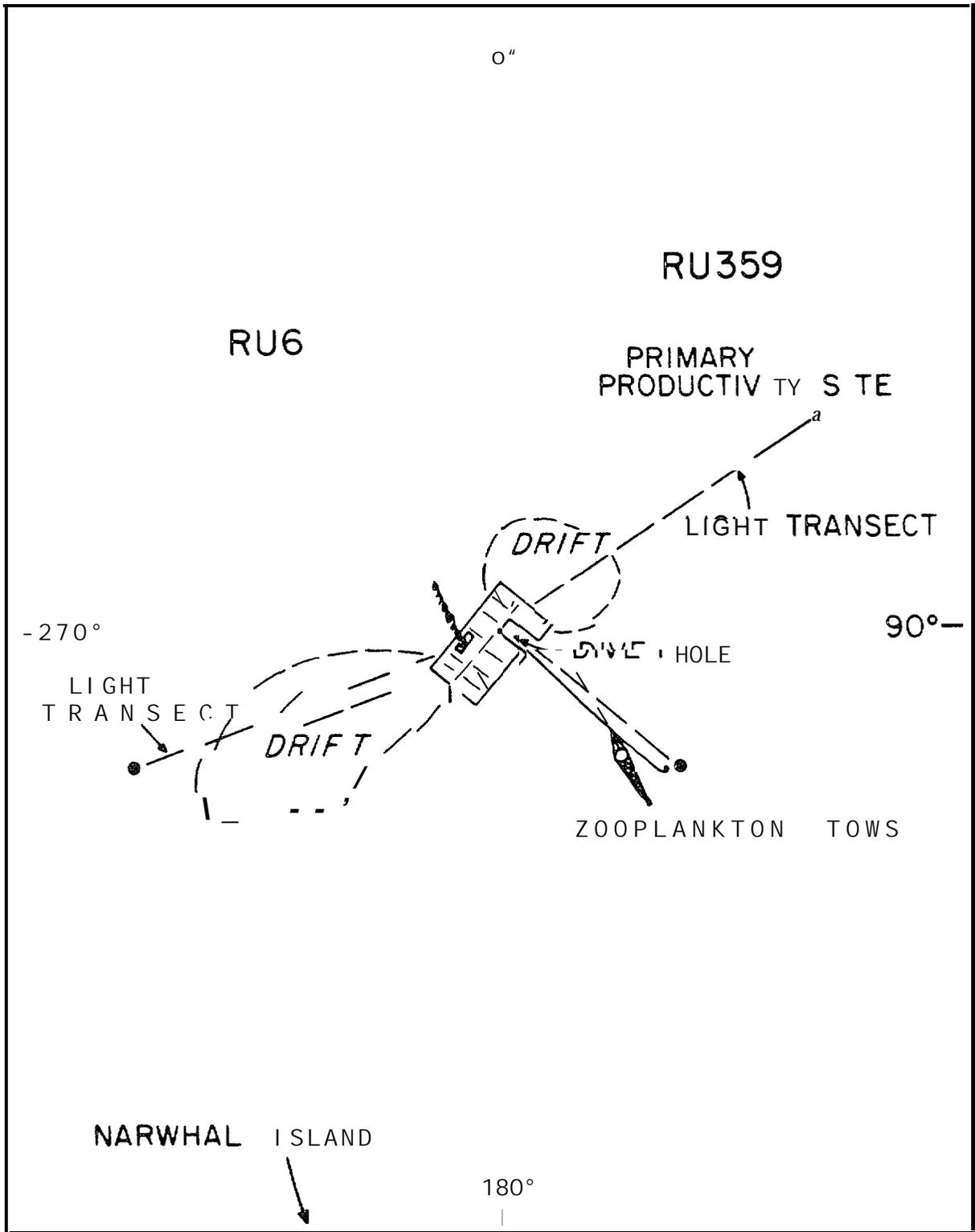


Fig. 2. Schematic diagram of the sampling site off Narwhal Island, spring 1980.

The **benthic microalgae** are those organisms, usually pennate diatoms, that live attached to or between sediment particles on the sea bed. This community may consist of patches of solitary, motile diatoms, dispersed solitary, motile diatoms, or mats of diatoms where cells are held together in tough mucilaginous filaments.

The zooplankton community consists of those invertebrates that live in the water column. They are present all year with species, life cycle stages, and abundances varying with season.

Separation of these communities is often difficult because diatoms from the ice community may be found in the water column or on the sea bed. This problem is more pronounced with the larger invertebrates such as amphipods because they are more mobile and able to move from one site to another. In the following discussion, we have tried to separate the communities as much as possible and to distinguish between typical ice algae species that might be in the water column temporarily and true **planktonic** species.

## B. Sampling methods

### 1. Phytoplankton

#### a. November 1978

Samples were collected daily from 8-16 Nov at dive site 11. Water samples were collected using a plastic water sampling bottle lowered on a hand line. Samples were collected near the underside of the ice (0 m) and near the bottom (4.5 m). Samples for **phytoplankton** standing stock were poured into 250 ml glass jars and immediately preserved with ea. 10 ml 4% formaldehyde buffered with sodium acetate. The remainder of the water samples, usually 3 l, was kept in a cool place until they could be taken to the shore laboratory.

Water collected for plant pigment determinations was filtered through 47 mm, 0.45  $\mu\text{m}$  Millipore filters. Near the end of the filtration process, three drops of a saturated solution of  $\text{MgCO}_3$  were added and the filter tower was rinsed with filtered seawater. The filters were folded into quarters, placed in labeled glassine envelopes, and frozen in a desicator.

#### b. February 1979

Only one sample was collected during the period 12-17 Feb because of weather and logistics problems. Water samples were collected through a hole used by LGL and located ea. 300 m south of dive site 11. Sampling was done using a plastic water sampling bottle lowered on a hand line. Sampling depths were 0 and 4.5 m. The **phytoplankton** standing stock samples were poured into 250 ml glass jars and preserved with ea. 10 ml 4% formaldehyde buffered with sodium acetate. The samples for plant pigment analysis were kept cool until they could be filtered on shore. The samples were filtered through 47 mm, 0.45  $\mu\text{m}$  Millipore filters. Three drops of a saturated solution of  $\text{MgCO}_3$  were added near the end of the filtration period, the filter tower was washed with filtered seawater, the

filter was removed, folded into quarters, placed in a labeled glassine envelope, and frozen in a desiccator.

c. March 1979

Samples were collected five times during the period 11-16 Mar at dive site 11. Samples for **phytoplankton** standing stock and plant pigment determinations were collected at 0 and 4 m using a plastic sampling bottle lowered on a hand line. The standing stock samples were drained into 250 ml glass jars and immediately preserved with ea. 10 ml 4% formaldehyde buffered with sodium acetate. The samples for plant pigment determinations were drained into 4 l polyethylene bottles and kept in a cool place until taken to the shore laboratory where they were filtered through 47 mm, 0.45  $\mu\text{m}$  Millipore filters. Three drops of a saturated solution of  $\text{MgCO}_3$  were added near the end of the filtration and the filter tower was washed down with filtered seawater. The **filter** was removed, folded into quarters, placed in a labeled glassine envelope, and frozen in a **desiccator**.

d. May 1979

Water samples were collected in 2 l polyethylene bottles from just under the ice (0 m) and near the bottom (4 m). Portions of these samples were poured into 60 ml reagent bottles, two light and one dark bottle for each depth, and inoculated with 2 ml  $\text{Na}_2\text{H}^{14}\text{CO}_3$  solution (ea. 5  $\mu\text{Ci}$ ). The samples were incubated *in situ* by attaching the bottles to a line suspended from the bottom of the ice. Another portion of the water sample was poured into a 250 ml jar and preserved with 5-10 ml 4% formaldehyde for a phytoplankton standing stock sample. The remainder of the sample, usually about 1.5 l, was returned to the shore laboratory.

At the shore laboratory, the remainder of the water sample was filtered through 47 mm, 0.45  $\mu\text{m}$  Millipore filters and the filters frozen for determination of plant pigments. Some of the filtered water was put into 250 ml polyethylene bottles to be used to determine salinity and some filtered water was put into 125 ml polyethylene bottles and frozen to be used to determine nutrient concentrations.

The primary productivity samples were **all** filtered through 25 mm, 0.45  $\mu\text{m}$  Millipore filters which were rinsed with 5 ml 0.01 N HCl and 5 ml filtered seawater before being placed in labeled glass scintillation vials.

All samples were returned to Seattle for analysis.

e. April-June 1980

Water samples for **phytoplankton** studies were collected with a PVC sampling bottle from just below the ice (0 m) and from 1 m above the bottom (7 m). Two-liter polyethylene bottles were rinsed and filled with water from each depth and a portion was used immediately for primary productivity experiments. The remainder of each sample was kept cool and dark in an ice chest until returned to the shore laboratory for analysis of plant pigments; portions were also preserved for standing

stocks, nutrient, and salinity determinations.

To determine rates of primary productivity, 60 ml glass-stoppered reagent bottles (two light, one dark for each depth) were rinsed and filled to the shoulder with sample. Each bottle was inoculated with 2 ml  $^{14}\text{C}$ -bicarbonate solution (ea. 5  $\mu\text{Ci}$ ), stoppered, and mixed. Samples were incubated for 3-4 hr at the sampling depths in clear plastic tubes suspended from a line anchored to the ice with an ice piton. Dark bottles were incubated in a darkened chamber at 0 m depth. Light, measured within the diving shelter, was comparable to under ice levels which reduced the problem of light-shock when bringing the samples to the surface. At the end of the incubation period, the samples were retrieved and kept in a darkened ice chest until processed at the shore laboratory, usually within 1-2 hr.

At the shore laboratory, primary productivity samples were filtered through 25 mm, 0.45  $\mu\text{m}$  Millipore filters, rinsed with 5 ml 0.01 N HCl and filtered seawater, and placed in labeled glass scintillation vials that were returned to Seattle for analysis. The 2 l polyethylene bottle containing water from each depth was shaken and 250 ml poured into 250 ml glass jars and preserved with 10 ml 4% buffered formaldehyde for standing stock analysis.

One liter of water from each sampling depth was filtered through a 47 mm, 0.45  $\mu\text{m}$  Millipore filter for pigment analysis. After ea. 100 ml of sample had filtered, filtration was stopped and the filtrate discarded. Filtration was continued until ea. 5 ml remained in the filter tower. Some of the filtrate was put into a 250 ml polyethylene bottle for later salinity determination and some was put into a 125 ml polyethylene bottle and frozen to be used to determine nutrient concentrations. Two drops of  $\text{MgCO}_3$  suspension were added to the filter tower and filtration continued until the filter was just dry. The tower was rinsed with filtered seawater, the filter was removed and folded into quarters, placed in a labeled glassine envelope, and stored frozen in a desiccator until pigment determinations were made within two weeks.

## 2. Ice algae

### a. May 1979

The ice algae were sampled by SCUBA divers using a combination incubation chamber-sampler used in previous studies (Clasby *et al.* 1973; Alexander *et al.* 1974). The chamber was constructed of 4.8 cm diameter plexiglass core tube lining 4 cm in length. The area of this sampler was 18.10  $\text{cm}^2$  and the volume 70 ml. One end was closed with a plexiglass plate fitted with a rubber septum, and the top of the sampler was serrated to cut into the ice. To place the chamber, a diver removed the septum, which allowed water to evacuate, and screwed the sampler into the underside of the ice to a depth of 2 cm. The septum was then replaced and a syringe used to inoculate the chamber with 2 ml  $^{14}\text{C}$ -bicarbonate solution (ea. 5  $\mu\text{Ci}$ ). In order to keep the  $^{14}\text{C}$  solution from freezing in the hypodermic syringe, each syringe filled with  $^{14}\text{C}$  solution was placed in a plastic container partially filled with hot water which the diver

took down to the experimental site. The syringe was pumped several times to help insure mixing of the isotope with the ice algae. Two light and one dark chamber were used. After a 3-4 hr incubation period, a heavy, metal spatula was used to chip away ice from around the chamber and sever the top of the core. The sample was retained in the chamber by a core cap. Dark uptake rates were determined in a darkened chamber that was capped and suspended from an ice piton immediately following inoculation. These chambers were also used to collect samples for plant pigment, standing stock, nutrient, and salinity determinations. Following retrieval, the ice cores were transferred to 250 ml glass jars. Primary productivity samples were immediately preserved with 5 ml 4% formaldehyde buffered with sodium acetate to prevent further uptake of the isotope by the cells. One additional core was **immediately** preserved with 5 ml 4% buffered formaldehyde to be used for standing stock analysis. The remaining cores were returned to the shore laboratory for further processing.

At the shore laboratory, primary productivity samples were filtered through 25 mm, 0.45  $\mu\text{m}$  Millipore filters, rinsed with 5 ml 0.01 N HCl and 5 ml filtered seawater, and placed in labeled scintillation vials for determination of carbon uptake. The remaining cores were filtered through 47 mm, 0.45  $\mu\text{m}$  Millipore filters and the filters were frozen for pigment analysis. The water was put into two 125 ml polyethylene bottles; one bottle was frozen to be used for nutrient determinations and one was to be used for salinity determination. All samples were returned to Seattle for analysis.

b. April-June 1980

For the spring 1980 sampling period, the ice incubation chamber was redesigned to accommodate a greater range of ice conditions and to minimize sample loss during core extraction and capping (see Appendix I). The new chamber has an area of 20.43  $\text{cm}^2$  and a volume of 85 ml.

Two new features were incorporated into this chamber. It was provided with a holder equipped with four threaded stainless steel pins adjusted to protrude ca. 2 cm from the chamber mouth. The chamber could then be hammered into the ice where the pins would anchor it securely. In addition, a scraper was designed with a locking pin that fit into a guide in the holder. At the end of the incubation period while the chamber was still anchored to the ice, the pin was started into the guide and the core severed as the scraper was pushed into place, sealing the chamber mouth. The scraper was secured by a handle on the bottom of the holder which was screwed tightly against the pin. The chamber can be returned to the surface with little sample loss. As an added precaution when returning the chambers to the surface, the scraper was held tightly against the chamber mouth to prevent leakage.

To measure dark uptake, a darkened chamber was hammered into the ice and the scraper inserted to enclose the ice sample prior to injecting the isotope. This allowed the chamber to remain in place during the incubation period. As the added weight of the scraper had a tendency to pull the sampler from the ice, a donut-shaped float was placed over the handle of

dark chambers to provide additional security.

Following retrieval, the primary productivity samples were immediately transferred to 250 ml opaque jars and two drops of 0.4%  $\text{HgCl}_2$  were added to **kill** the **cells** and prevent further uptake of the isotope. Five additional cores were taken to determine standing stock, plant pigments, particulate carbon, nutrient concentrations, and salinity. All samples were transferred to 250 ml glass jars and kept in the dark in an ice chest until processing at the shore laboratory within 2-3 hr. The additional cores were taken after the incubation period to minimize the time between collecting and processing.

At the shore laboratory the primary productivity samples were filtered onto 25 mm, 0.45  $\mu\text{m}$  Millipore filters, rinsed with 0.01 N HCl and filtered seawater, and placed in glass scintillation vials. Three ice cores were used for determination of plant pigments. Each core was allowed to melt and was filtered onto a 47 mm, 0.45  $\mu\text{m}$  Millipore filter. After ca. 5 ml had filtered, filtration was stopped and the filtrate discarded. Filtration was continued until ea. 5 ml remained in the filter tower. This filtrate was divided equally between two 125 ml polyethylene bottles for nutrient and salinity determinations, the filtrate from all three cores being combined. Two drops of  $\text{MgCO}_3$  suspension were added to the filter tower and filtration continued until the filter was just dry. The tower was rinsed with 5 ml filtered seawater and obvious animals (> 1 mm) were carefully removed. The filters were folded into quarters, placed in labeled glassine envelopes, and stored frozen in a desiccator until pigment determinations were made within two weeks. Nutrient samples were immediately frozen. The core to be used for standing stock determination was preserved with 10 ml 4% formaldehyde buffered with sodium acetate.

One ice core, to be used by RU 537 for particulate carbon determination, was filtered through a 25 mm Gelman glass fiber filter provided by RU 537. The sample was filtered to dryness and the tower rinsed with 5 ml filtered seawater. Conspicuous animals (> 1 mm) were removed with forceps and the filter, folded into quarters, was placed in a labeled glassine envelope and stored frozen.

### 3. Benthic microalgae (spring 1980)

Benthic primary productivity was measured using field techniques described by Matheke (1973). The incubation chambers consisted of 3.4 cm diameter plastic cylinders closed at one end with a plastic sheet drilled to accept a No. 00 rubber stopper. A sidearm with a rubber sleeve-type serum bottle stopper was located near the top of each cylinder. The bottom of the cylinder was beveled to minimize disturbance of the sediment when the diver placed it in the bottom. With the rubber stopper removed, the cylinder was pushed ca. one-half way into the sediment. The rubber stopper was inserted into the top of the chamber and 2 ml  $^{14}\text{C}$ -bicarbonate solution (ea. 5  $\mu\text{Ci}$ ) was injected through the serum bottle stopper with a syringe. The chambers were then pushed further into the sediment to ensure penetration of the isotope. The isotope was detected in the 1-2 mm layer when incubation chambers were treated this way (Leach 1970). Two light and one dark chamber were used. After a 3-4 hr incubation period,

the chambers were capped with rubber stoppers and returned to the surface where two drops of concentrated  $H_3PO_4$  were added to kill the algae. The cores were left in the incubation chambers and stored upright in an ice chest until processing 2-3 hr later.

On shore, the water was suctioned from the top of the core, the volume recorded, and then filtered through a 47 mm **Whatman** GFC glass fiber filter. The tower was rinsed with 5-10 ml filtered seawater, the filter was removed, folded into quarters, and placed in a labeled plastic petri dish. The top 1 cm of sediment was cut off with a sharp spatula and transferred to a labeled petri dish. Filter and sediment samples were kept frozen for later analysis.

Samples were collected for pigment and standing stock analysis using 3.8 cm diameter plastic core tubes beveled at the bottom. The cores were pushed into the sediment to a depth of *ca.* 5 cm, the upper end was capped with a rubber stopper, and the corer withdrawn until the bottom of the corer could be closed with another rubber stopper. In the laboratory, the supernatant water was drawn off and the top 1 cm of each core was removed. One sample was placed in a plastic petri dish and frozen for later pigment analysis; another was to be used for sediment size analysis. One core section was transferred to a 250 ml glass jar to which 25 ml filtered seawater and 25 ml 4% formaldehyde buffered with sodium acetate were added to be used for standing stock analysis.

#### 4. Zooplankton

##### a. November 1978

Zooplankton samples were collected using a 0.75 m ring net with a mesh size of 308  $\mu m$  and an open area ratio of 2:1. Vertical tows were made by lowering the net to the bottom and retrieving by hand at a constant rate. Horizontal tows were made by extending a stationary line from the sampling hole to an ice piton located on the surface *ea.* 12 m away. The net ring was clipped to a pulley on this line, pulled backward to the ice piton, and then forward to the sampling hole. Slack in the stationary line caused an unknown amount of deviation from a constant depth of tow, but the deviation was assumed to be minimal and was ignored. All net tows were timed with a stopwatch to obtain an approximate speed of tow.

The net was washed by dipping it several times in the hydrohole. The collection cup was then placed in a plastic bucket and removed from the net. Samples were warmed slowly when ice occurred in the collection cup. Samples were concentrated by gently swirling the collection cup and were then poured into 250 ml glass jars. A label with the collection data was placed in the jar and the sample was preserved with 13 ml 37% formaldehyde buffered with 5 ml each saturated sodium acetate and sodium borate solutions. Seawater was added if necessary to fill the jar and the jar was tightly capped for storage and shipping to Seattle.

A 0.25 m ring net with mesh size of 46  $\mu m$  was used to scrape the underside of the ice for epontic organisms. In the first attempt, the net was

towed behind a diver swimming immediately under the ice, but swimming speed was not fast enough to keep the net horizontal and against the underside of the ice. On the second try, two 25,0 ml jars partially filled with water were taped to one leg of the net bridle and to the collection jar to provide flotation, but the diver still could not keep the net against the ice. An ice sample was collected by leaving the flotation jars empty and increasing the towing speed by pulling the diver in by his safety line. Samples were poured into 250 ml jars and preserved with 20 ml 4% formaldehyde buffered with sodium acetate.

b. February 1979

No zooplankton samples were collected because of weather and logistics problems.

c. March 1979

Zooplankton samples were collected with a 0.75 m ring net with a mesh size of 209  $\mu\text{m}$ . The net was lowered to the bottom and vertically hauled to the surface by hand. Hauls were timed using a stopwatch to obtain the approximate speed of tow. The net was washed by dipping it several times in the hydrohole and the samples were drained into a plastic bucket. If necessary, the samples were warmed slowly to melt any ice. The samples were concentrated by gently swirling in the net collection cup and were preserved in 250 ml jars with 10 ml 37% formaldehyde buffered with 5 ml each saturated sodium acetate and sodium borate solutions. Seawater was added if necessary to fill the jars and they were tightly capped for storage.

d. May 1979

One zooplankton sample was collected with a 0.5 m ring net, mesh size 209  $\mu\text{m}$ . The net was lowered to the bottom and vertically hauled to the surface. The net was washed by dipping it several times in the hydrohole. The sample was concentrated by gently swirling in the net collection cup and was preserved in a 250 ml jar with 10 ml 37% formaldehyde buffered with sodium acetate.

e. Spring 1980

Zooplankton was sampled with a 0.75 m ring net having a mesh size of 308  $\mu\text{m}$ . The net ring was attached to a line and pulley system anchored to a post placed through the ice 14 m from the dive hole. The net was lowered through the dive hole and hauled horizontally as quickly as possible to the pulley and back, fishing at an average depth of 2 m. Net tows were timed to obtain an approximate speed of tow (ca.  $0.3 \text{ m sec}^{-1}$ ). The net was washed by dipping it several times in the dive hole. The sample cup was removed and warmed slowly if much ice was present. Samples were concentrated by gently swirling the collection cup and then poured into 250 ml glass jars. Samples were stored in an ice chest until processed on shore where a label was placed in the jar and the sample was preserved with 25 ml 37% formaldehyde buffered with sodium acetate.

#### 5. 24 hr primary productivity studies (spring 1980)

At ea. bi-weekly intervals, replicate water, ice, and benthic primary productivity incubation chambers were placed and inoculated. One set was allowed to incubate for the normal 4 hr period as part of the regular sampling regime; the second set was retrieved on the following day after a 24 hr incubation period. All samples were treated as described for the 4 hr incubations.

#### 6. Light (spring 1980)

Light intensity was measured with a LI-COR underwater quantum sensor, Model LI-192S, and a quantum radiometer-photometer, Model LI-185A, (LI-COR, Inc., Lincoln, NE.). This sensor measures light intensity in the 400-700 nm waveband, which is the waveband used by plants for photosynthesis. Measurements were in microeinsteins  $m^{-2} \text{ sec}^{-1}$ , where one microeinstein equals  $6.02 \times 10^{17}$  photons. Accuracy is stated as  $\pm 7\%$ . This meter was intercalibrated on 28 May 1980 with a Protomatic Underwater Photometer used by RU 537 that measured light intensity in lux.

Submarine light was measured immediately after placement of the  $^{14}C$  incubation chambers and again just prior to their retrieval. All measurements were made within 1 m of the chambers, and care was taken to avoid errors due to shading and sediment suspended by the diver. With the sensor directed upward, light was measured directly beneath the ice, both before and after removal of the ice algal layer. Light reaching the benthos was measured near the bottom directly above the  $^{14}C$  incubation chambers. Surface light outside the dive shelter was also measured, with the sensor held vertically ea. 2 m above the snow surface.

To assess the effect of snow depth on light penetration and algal growth, a series of transects was begun on 28 Apr and continued at ea. bi-weekly intervals through 3 Jun. Transects were taken in two locations: through a semi-permanent snow drift that formed in the lee of the tent, and through the area from which the majority of the ice samples were collected (ea. 15 m north of the tent). Each transect was marked by a permanent post placed through the ice and visible from both the surface and underside of the ice. A line marked at 0.5 m intervals was anchored to the reference post and secured to the tent frame. The surface light intensity was recorded, and snow depth measured, at 1 m intervals along the transect line for a distance of 25 m. Measurements were made at 0.5 m intervals along the portion of the transect that passed through the drift. Immediately following the surface transect, the line was removed and secured by a diver to the reference post under the ice and to the tent frame. Light intensity was measured at the same points along the line as the surface transect, both before and after removal of the ice algal layer.

#### 7. Surface weather observations (spring 1980)

Surface weather observations were taken within one hr of the placement of productivity chambers. Surface water temperature was measured with a laboratory thermometer held just beneath the surface of the water in the dive hole, and read while submerged. Air temperature

was measured with the same thermometer suspended 0.5 m from the tent on the windward side in the shade. Five minutes were allowed for equilibration. The wind direction was determined using a hand held compass, and speed was estimated using Deadhorse Airport weather reports and the helicopter air speed indicator as guides. Local weather, cloud type, and percentage cover were also recorded. Ice thickness was recorded by divers from a reference post marked at 1 cm intervals which was placed through the ice (Appendix II-1).

c. Analytical methods

1. Ice algae and phytoplankton

a. Primary productivity

Primary productivity samples were counted in Seattle using a Packard **Tri-Carb** Liquid Scintillation Spectrometer with 10 ml Aquasol (New England Nuclear, Boston, MA.) as the scintillation cocktail. Samples were counted for 50 min or to 50,000 counts. Phytoplankton carbon uptake was calculated using the equation:

$$\text{Carbon uptake (mg C m}^{-3} \text{ hr}^{-1}) = \frac{(L-D) (W) (1.05)}{(R) (T)}$$

where L = average of two light bottle counts in disintegrations per minute (dpm); D = dark bottle count (dpm); W = weight of carbonate carbon in mg C m<sup>-3</sup> (determined by multiplying the salinity, ‰, X 810 [G. C. Anderson pers. comm.]); 1.05 = <sup>14</sup>C isotope factor; R = activity of the <sup>14</sup>C added; and T = incubation time (hr).

Precision at the 1.5 g C m<sup>-3</sup> hr<sup>-1</sup> level is in the range: mean of n determinations is ± 0.15/n<sup>1/2</sup> mg C m<sup>-3</sup> hr<sup>-1</sup> (7 hr incubations, 5 μCi added) (Strickland and Parsons 1968).

Ice algal carbon uptake was calculated using the equation:

$$\text{Carbon uptake (mg C m}^{-2} \text{ hr}^{-1}) = \frac{(L-D) (W) (1.05)}{(R) (A) (T)}$$

where L = average of two light bottle counts in disintegrations per minute (dpm); D = dark bottle count (dpm); W = weight of inorganic carbon per sample; 1.05 = <sup>14</sup>C isotope factor; R = activity of the <sup>14</sup>C added; A = area of core (m<sup>2</sup>); and T = incubation time (hr).

b. Plant pigments

Filters were ground in 7-9 ml 90% acetone with a **teflon** tissue grinder for about 4 min. The samples were then centrifuged for 10 min. The supernatant liquid was decanted into a clean centrifuge tube, 1 ml 90% acetone was added to the filter residue and it was centrifuged again for about 5 min. The liquid was added to the first supernatant liquid and the total sample centrifuged again for about 10 min.

The extracts were made up to 10 ml with 90% acetone and measured in a Turner Model 111 **fluorometer** with the scale zeroed against 90% acetone. A second measurement was made after 2 drops of 0.1 N HCl were added to the extract. Chlorophyll *a* and phaeopigment **concentrations** were calculated using the equations:

$$\text{mg Chl } a \text{ m}^{-3} = \frac{\text{Fe/Faux}}{\frac{(\text{Fo/Fa}_{\text{max}}) - 1}{K} \cdot L}$$

$$\text{mg Phaeo } \text{m}^{-3} = \frac{\frac{\text{Fo/Fa}_{\text{max}}}{(\text{Fo/Fa}_{\text{max}}) - 1} \cdot K \cdot [\text{Fo/Fa}_{\text{max}} (\text{Fa}) - \text{Fa}]}{L}$$

where **Fo** = **fluorometer** reading before acidification; **Fa** = **fluorometer** reading after acidification;  $\text{Fo/Fa}_{\text{max}}$  = maximum chlorophyll/phaeopigment ratio (1.91); **K** = calibration **constant** (assumes 10 ml extract); **L** = volume of water filtered in liters (Lorenzen 1966).

To express the concentration of plant pigments obtained from ice cores as mg pigment  $\text{m}^{-2}$ , the expression (A x 1000) was substituted for the volume of water filtered (L) in the above equations. **A** = area of the core ( $\text{m}^2$ ).

The limit of detection depends on the volume of water filtered and the sensitivity of the **fluorometer**. About 0.01 mg chl *a*  $\text{m}^{-3}$  should be detectable with a 2 l sample.

#### c. Nutrients and salinity

Nutrient and salinity samples were returned to the University of Washington, Department of Oceanography Chemistry Laboratory for analysis. The nutrient samples were analyzed using autoanalyzer techniques; salinity samples were analyzed using a whetstone bridge (Pavlou 1972).

#### d. Standing stock

Standing stock samples were analyzed with a Zeiss phase contrast inverted microscope following the method of Utermöhl (1931). Large and rare **phytoplankton** organisms (> 100  $\mu\text{m}$ ) were counted at 156 X magnification in 50 ml Zeiss counting chambers and small, abundant organisms (< 100  $\mu\text{m}$ ) were counted at 390 X magnification in 5 ml Zeiss counting chambers. Usually 1/5 of the chamber was counted.

Ice algae were counted at 390 X magnification in 5 ml Zeiss chambers; usually 1/10 of the chamber was counted. Samples with very high density were diluted 1:5 with distilled water before settling. Many species are difficult or impossible to identify in water mounts, therefore a second set of **subsamples** was acid cleaned and permanently mounted in Euparal vert

resin on microscope slides. Higher magnifications, up to 2000 X, could be used with these slides. Line drawings were made of some species to aid in identification.

References used to identify the phytoplankton and ice algae included Cleve and Grunow (1880); Cleve (1894-1895); Van Heurck (1896); Hustedt (1930, 1959-1962); Schiller (1933-1937); Cupp (1943); and Hendey (1964).

Species diversity of the ice algal community was calculated using the Shannon-Wiener diversity index (H), which is widely used in phytoplankton community studies (Fager 1972; Poole 1974):

$$H = - \sum_{i=1}^s (n_i/N) \ln (n_i/N)$$

where  $n_i$  = number of cells of the  $i$ th species;  $N$  = total number of cells; and  $s$  = number of species.

## 2. Benthic microalgae

### a. Primary Productivity

The amount of  $^{14}\text{C}$  incorporated by benthic microorganisms was determined at the University of Louisville, Louisville, KY, using the wet oxidation technique described by Atlas and Hubbard (1974). Carbon uptake was calculated using the equation:

$$\text{Carbon uptake (mg C m}^{-2} \text{ hr}^{-1}) = \frac{(L-D) (W) (1.05)}{(R) (A) (T)}$$

where  $L$  = average of two light bottle counts in disintegrations per minute (dpm);  $D$  = dark bottle count (dpm);  $W$  = inorganic carbon per sample;  $1.05$  =  $^{14}\text{C}$  isotope factor;  $R$  = activity of  $^{14}\text{C}$  added;  $A$  = sample area ( $\text{m}^2$ ); and  $T$  = incubation time (hr).

### b. Plant pigments

Before analysis, the samples were thawed in the dark at  $5^\circ\text{C}$ . Each sample was weighed and mixed in the petri dish and two subsamples (ca. 2 g) were removed and weighed. Subsamples were ground with a mortar and pestle for ca. 1 min in 3 ml 90% acetone, washed into a 15 ml centrifuge tube, and the volume brought to 15 ml with 90% acetone. The samples were extracted in the dark at  $5^\circ\text{C}$  for 17-20 hr, and were shaken 1 hr after the beginning of the extraction and at the end of the extraction period. Samples were centrifuged for 15 min, and the extract volume determined by subtracting the sediment volume from the total volume. Fluorescence was measured in a Turner Model 111 fluorometer with the scale zeroed against 90% acetone. A second measurement was made after acidification with 2 drops 1 N HCl. Chlorophyll a and phaeopigments were calculated using an adaptation of Lorenzen's equations (Lorenzen 1966):

$$\text{mg Chl } a \text{ m}^{-2} = \frac{\frac{F_0/F_{a_{\max}}}{(F_0/F_{a_{\max}}) - 1} \cdot (F_0 - F_a) \left(\frac{W_c}{W_s}\right) \left(\frac{V}{10}\right)}{1000 A}$$

$$\text{mg Phaeo } \text{m}^{-2} = \frac{\frac{F_0/F_{a_{\max}}}{(F_0/F_{a_{\max}}) - 1} \cdot K_x \cdot [F_0/F_{a_{\max}} \cdot F_a - F_0] \left(\frac{W_c}{W_s}\right) \left(\frac{V}{10}\right)}{1000 A}$$

where  $F_0$  = fluorometer reading before acidification;  $F_a$  = fluorometer reading after acidification;  $F_0/F_{a_{\max}}$  = maximum chlorophyll/phaeopigment ratio (1.89);  $K_x$  = calibration constant;  $A$  = area of the core sample ( $1.13 \times 10^{-3} \text{ m}^2$ );  $W_c$  = weight of core (g);  $W_s$  = weight of subsample (g); and  $V$  = volume of extract (ml).

### c. Standing stock

The top 1 cm of the benthic cores was rinsed into a graduated cylinder and diluted to 1 l with distilled water. The samples were mixed by vigorous stirring and bubbling air from a glass tube extending to the bottom of the cylinder. One ml subsamples were drawn from the middle of the cylinder with a pipette and added to 50 ml Zeiss counting chambers which were then filled with distilled water and allowed to settle for 24 hr. The samples were counted at 400 X magnification using a Zeiss phase contrast inverted microscope (Utermöhl 1931). Normally, 1/10 of the chamber was counted.

### 3. Zooplankton

All zooplankton samples were first sorted for large, rare organisms such as mysids, amphipods, euphausiids, shrimp, and fish eggs and larvae. The samples were split in a Folsom plankton splitter (McEwan *et al.* 1954) until a subsample containing ea. 100 specimens of the most abundant remaining taxa was obtained. Subsamples were successively sorted until at least 100 specimens of each taxon were counted and identified. Counts and identifications were done using dissecting microscopes. Identifications were done using dichotomous keys and by comparison with descriptions and illustrations in the literature.

For copepods, samples that had previously been sorted for larger animals were subsampled with a calibrated automatic pipette to obtain a subsample containing about 100 specimens of the most abundant copepod species. Copepods were identified, counted, and recorded by sex and copepodid stage.

The number of animals per 1000  $\text{m}^3$  was calculated using the equations:

$$V (\text{m}^3) = \text{haul length (m)} \times \text{mouth area (m}^2)$$

$$\text{Number (1000 m}^3) = \frac{(A) (1000)}{V} \times 2^n$$

where V = volume of water filtered; A = number of animals counted; and n = number of times the sample was split.

References used to identify zooplankton are listed in Table 1.

#### 4. Light

Percentage surface light was calculated according to the equation:

$$\% \text{ surface} = \frac{I}{I_0} \times 100$$

where I = light intensity ( $\mu\text{E m}^{-2} \text{ sec}^{-1}$ ) measured at depth;  $I_0$  = incident radiation ( $\mu\text{E m}^{-2} \text{ sec}^{-1}$ ) measured above the ice.

The diffuse attenuation coefficient  $k_{(m-1)}$ , was calculated from the relationship:

$$\frac{I}{I_0} = 10^{-kz}$$

or

$$k = \frac{-\log \frac{I}{I_0}}{z}$$

where I = light intensity ( $\mu\text{E m}^{-2} \text{ sec}^{-1}$ ) measured in the bottom ice above the ice algal layer;  $I_0$  = incident radiation ( $\mu\text{E m}^{-2} \text{ sec}^{-1}$ ) measured above the ice; and Z = total thickness of the ice plus snow depth (m).

In the text, the diffuse attenuation coefficient ( $k_{m-1}$ ) is referred to as the extinction coefficient.

## VI. Results

### A. Stefansson Sound, 1978-1979

#### 1. Phytoplankton and ice algae

Phytoplankton levels in Stefansson Sound were low during the winter period (Tables 2-3). In November, 1978, unidentified flagellates, mostly  $< 6 \mu\text{m}$  in diameter, were the most common organisms. A few diatoms, including spores of *Chaetoceros* spp., and cells of *Navicula* spp. and *Nitzschia* spp., were also present. Although the diatoms contained **chloroplasts**, they did not appear to be healthy. Chlorophyll a levels were low.

Phytoplankton levels remained low in February and March with unidentified small flagellates being the most numerous organisms. A few pennate diatoms were also present. In February, there were many small detritus

Table 1. References used to identify zooplankton from Narwhal Island, spring 1980.

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Cnidaria - Hydrozoa

**Kramp**, P. L., 1961

Shirley, D. W., and Y. M. Leung, 1970

Ctenophora

**Leung**, Y. M., 1970b

Arthropoda - **Crustacea** - Copepoda

Heron, G. A., and D. M. Damkaer, 1976

Jaschnov, W. A., 1948

Lang, K., 1948

Lindberg, K., 1953

Sars, G. O., 1903-1911

Sars, G. O., 1913-1918

Sars, G. O., 1921

Arthropods - **Crustacea** - Mysidacea

Banner, A. H., 1948a, b

**Leung**, Y. M., 1972b

**Sars**, G. O., 1870

Arthropoda - **Crustacea** - Amphipoda

Bernard, J. L., 1969

Gurjanova, E., 1951

Sars, G. O., 1895

Tencati, J. R., 1970

Arthropoda - Crustacea - Euphausiacea

Banner, A. H., 1950

**Leung**, Y. M., 1970a

**Zimmer**, C., 1933

Chaetognatha

Dawson, J. K., 1971

Chordata - Larvacea

**Leung**, Y. M., 1972a

Lohmann, H., 1933

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Table 2. Phytoplankton and ice algae data from Stefansson Sound, 1978-1979.

Date	Standing Stock (Total cells/liter)		Chl a (mg m <sup>-3</sup> ) (mg m <sup>-2</sup> )			Phaeo (mg m <sup>-3</sup> ) (mg m <sup>-2</sup> )			Prim Prod (mg C m <sup>-3</sup> hr <sup>-1</sup> ) (mg C m <sup>-2</sup> hr <sup>-1</sup> )		
	0 m	4 m	0m	4m	ice	0 m	4 m	ice	0m	4m	ice
8 Nov 78	26000	14000	0.06			0.07					
9	24000	18000	0.02	0.02		0.12	0.12				
10			0.06	0.06		0.06	0.08				
11			0.05	0.05		0.04	0.05				
12			0.06	0.04		0.07	0.06				
13			0.06	0.04		0.05	0.06				
14			0.07	0.04		0.05	0.05				
15			0.05	0.06		0.06	0.06				
16	46000	46000	0.06	0.06		0.05	0.05				
15 Feb 79	36000	22000	0.02	0.01		0.07	0.04				
12 Mar 79	46000	34000	0.01	0.00		0.03	0.02				
13			0.00	0.01		0.02	0.03				
14 ice core		38000	0.00	0.01		0.03	0.03				
15			0.01	0.01		0.03	0.07				
16	60000	82000	0.01	0.01		0.03	0.03				
15 May 79		3 ice cores*			2.87			4.32			1.50
18	162000	38000*	0.42	0.17		1.13	0.24		0.16	0.12	1.42
		3 ice cores*			2.70			3.36			
19			0.67	0.24		1.05	0.43		0.16	0.80	0.31
		3 ice cores*			2.53			2.83			
20	208000	36000	1.19	0.23		0.89	0.33		0.11	0.26	1.42
	ice core	23070000									
		4 ice cores*			3.01			1.99			

\* average values

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Table 3. Phytoplankton and ice core standing stock (cells  $\mu\text{m}^{-3}$ ) from Stefansson Sound, 1978-1979.

Taxon	8 Nov 78		9 Nov 78		16 Nov 78		15 Feb 79		12 Mar 79	
	Om	4m	Om	4m	0 m	4m	Om	4m	Om	4m
Diatoms										
<i>Amphiprora</i> spp.										
<i>Amphiprora hyperborea</i>										
<i>Chaetoceros</i> spp.	2000		2000		8000		2000			2000
<i>Chaetoceros septentrionalis</i>										
<i>Cylindrotheca closterium</i>		2000					2000			
<i>Gyrosigma</i> spp.										
<i>Limnophora</i> spp.										
<i>Melosira</i> spp.										
<i>Navicula</i> spp.				2000						
<i>Navicula marina</i>										
<i>Navicula pelagica</i>										
<i>Nitzschia</i> spp.										
<i>Nitzschia cylindrus</i>										
<i>Nitzschia delicatissima</i>										
<i>Nitzschia seriata</i> cf.										
<i>Thalassiosira</i> spp.										
<i>Thalassiosira Antarctica</i> cf.										
<i>Thalassiosira gravida</i>										
<i>Tropidoneis</i> sp.										
Unidentified pennate diatoms										
< 10 $\mu\text{m}$		2000								
11 - 20 $\mu\text{m}$										
21 - 30 $\mu\text{m}$										
31 - 40 $\mu\text{m}$										
41 - 50 $\mu\text{m}$										
51 - 75 $\mu\text{m}$										
76 - 100 $\mu\text{m}$										
101 - 150 $\mu\text{m}$										

Table 3. (cent. )

Taxon	8 Nov 78		9 Nov 78		16 Nov 78		15 Feb 79		12 Mar '79	
	Om	4m	Om	4m	Om	4m	Om	4m	Om	4m
Unidentified flagellates										
< 10 $\mu\text{m}$	20000	10000	20000	14000	44000	36000	32000	18000	40000	22000
11 - 20 $\mu\text{m}$					2000				2000	
21 - 30 $\mu\text{m}$	2000									
31 - 40 $\mu\text{m}$										
41 - 50 $\mu\text{m}$										
Identified flagellates										
<i>Calycomonas gracilis</i>										
Unidentified choanoflagellates							2000		4000	6000
Unidentified cryptomonads										
Chrysophyte										
<i>Dinobryon petiolatum</i>										
Euglenophyta										
Unidentified euglenoid cf.										
<i>Euptreptiella</i> sp. cf.										
<i>Urceolus</i> Sp.										
Chlorophyta										
<i>Platymonas</i> sp. cf.	2000		2000							
Pyrrophyta										
Unidentified dinoflagellates				2000		2000	2000			
<i>Gonyaulax</i> sp.										
<i>Peridinium</i> spp.										

Table 3. (cont. )

Taxon	14 Mar 79		16 Mar 79		18 May 79		20 May 79		20 May 79	
	ice core		Om	4m	Om	4m	ice core	Om	4m	
Diatoms										
<i>Amphiprora</i> spp.							50000			
<i>Amphiprora hyperborea</i>							60000	6000		
<i>Chaetoceros</i> spp.	4000						280000	4000		
<i>Chaetoceros septentrionalis</i>								2000		
<i>Cylindrotheca closterium</i>			2000		4000		80000	12000	4000	
<i>Gyrosigma</i> spp.						2000	130000	2000		
<i>Licmophora</i> spp.							530000	2000		
<i>Melosira</i> spp.							40000			
<i>Navicula</i> spp.	2000						550000	2000		
<i>Navicula marina</i>							80000			
<i>Navicula pelagica</i>							860000			
<i>Nitzschia</i> spp.	2000		2000	2000	8000		2560000	10000		
<i>Nitzschia cylindrus</i>	2000				14000		5880000			
<i>Nitzschia delicatissima</i>								4000		
<i>Nitzschia frigida</i>						6000	6080000	14000		
<i>Nitzschia seriata</i> cf.						6000		12000		
<i>Thalassiosira</i> spp.	6000									
<i>Thalassiosira antarctica</i>	12000									
<i>Thalassiosira gravida</i>										
<i>Tropidoneis</i> sp.							10000			
Unidentified pennate diatoms										
< 10 $\mu$ m	2000			2000	2000	2000	190000	2000		
11 - 20 $\mu$ m	6000					2000	850000			
21 - 30 $\mu$ m							870000	4000		
31 - 40 $\mu$ m				8000	4000		320000			
41 - 50 $\mu$ m							200000	2000	2000	
51 - 75 $\mu$ m							350000			
76 - 100 $\mu$ m							30000			
101 - 150 $\mu$ m							80000			

Table 3. (cont. )

Taxon	14 Mar 79		16 Mar 79		18 May 79		20 May 79		20 May 79	
	ice core		0m	4m	0m	4m	ice core	0m	4m	
Unidentified flagellates										
< 10 $\mu\text{m}$	2000		46000	64000	84000	34000	2740000	98000	28000	
11 - 20 $\mu\text{m}$			2000		8000		320000	6000		
21 - 30 $\mu\text{m}$							20000	4000		
31 - 40 $\mu\text{m}$							10000	2000		
41 - 50 $\mu\text{m}$							20000			
Identified flagellates										
<i>Calycomonas gracilis</i>										2000
Unidentified choanoflagellates			6000							
Unidentified cryptomonads				2000			20000	2000		
Chrysophyte										
<i>Dinobryon petiolatum</i>								2000		
<b>Euglenophyta</b>										
Unidentified euglenoid cf.					2000					
<i>Euptreptiella</i> sp. cf.					2000		10000	2000		
<i>Urceolus</i> sp.							30000			
<b>Chlorophyta</b>										
<i>Platymonas</i> sp. cf.					4000		50000	2000		
<b>Pyrrophyta</b>										
Unidentified dinoflagellates			2000	4000	2000		60000	2000		
<i>Gonyaulax</i> sp.								2000		
<i>Peridinium</i> spp.					14000		20000	8000		

particles in the water sample collected from just beneath the ice (0 m) which made phytoplankton counting difficult. The detritus particles probably came from dirty brash ice that formed a thick layer on the underside of the ice (Dunton pers. comm.). Not as much detritus was found in the sample collected near the sea bed. Chlorophyll *a* levels were barely detectable.

By March, the number of individual diatom cells and the number of diatom species increased with species that are common in the spring beginning to appear. Chlorophyll *a* levels were still low.

One ice core collected by RU 6 on 14 Mar was analyzed. The core, about 30 cm long and 2.5 cm in diameter, was collected from the brash ice layer on the underside of the ice. *Navicula* sp., *Nitzschia* spp., and unidentified pennate diatoms were present, along with *Thalassiosira* spp. The large amount of detrital material made positive identification of the *Thalassiosira* spp. impossible.

By May, more diatom cells were present in the water column, including species of *Chaetoceros*, *Cylindrotheca*, *Navicula*, and *Nitzschia*. Unidentified flagellates, usually c 10  $\mu\text{m}$  in diameter, were abundant, along with a few cryptomonad, chrysophyte, and euglenoid species. Unidentified *Peridinium* spp. and other unidentified dinoflagellates were present in low numbers. Chlorophyll *a* levels in the water column were still low, but beginning to increase slightly.

An ice core collected on 20 May contained more than  $23 \times 10^6$  cells per liter, including diatoms and flagellates. *Nitzschia* spp. were the most abundant organisms with *Nitzschia frigida* and *N. cylindrus* comprising nearly 50% of the total population. Both of these species are common in the ice in the Barrow area with *N. frigida* found in large numbers only in the ice, while *N. cylindrus* is also a prominent component of the phytoplankton in spring (Alexander *et al.* 1974; Homer 1976). Other typical ice organisms found included *Eutreptiella* sp., and *Urceolus* sp. *Eutreptiella* sp. is sometimes found in the water column also, but only when ice is present (Homer unpubl. obs.). Neither of these species occurred in large numbers. Chytridiaceous fungi were found to be parasitizing some of the pennate diatoms.

Chlorophyll *a* levels in the ice cores were variable and phaeopigments were high (Table 2).

Primary productivity was low in the water column, averaging about  $0.15 \text{ mg C m}^{-3} \text{ hr}^{-1}$ . In the ice, primary productivity was much higher. On 15, 18, and 20 May, productivity was consistently near  $1.5 \text{ mg C m}^{-2} \text{ hr}^{-1}$ , but on 19 May, productivity was only  $0.3 \text{ mg C m}^{-2} \text{ hr}^{-1}$  probably because of the patchy distribution of the ice algae. On an areal basis ( $\text{mg C m}^{-2} \text{ hr}^{-1}$ ) ice algal primary production was approximately twice that of the water column.

## 2. Nutrients and salinity

Nutrient and salinity data from May 1979 are given in Table 4. On 18, 19, and 20 May, a lens of low salinity water (*ca.*

Table 4. Nutrient and salinity data from Stefansson Sound, May 1979. Where no number is present, no sample was taken.

Date	Nutrient Concentrations ( $\mu\text{g-at } \ell^{-1}$ )					Salinity ( $^{\circ}/\text{'00}$ )
	$\text{NO}_3$	$\text{NO}_2$	$\text{NH}_3$	$\text{PO}_4$	$\text{SiO}_4$	
15 May						
0 m						
4 m						
ice	1.35	0.14	2.68	1.38	19.90	
18 May						
0 m	1.55	0.04	1.07	0.20	24.06	18.28
4 m	4.69	0.17	0.84	1.42	13.34	35.20
ice	1.19	0.06	2.85	0.74	20.62	15.26
19 May						
0 m	1.57	0.06	1.68	0.39	26.27	18.32
4 m	4.72	0.16	0.24	0.95	13.23	35.19
ice	1.24	0.05	1.87	0.50	21.02	15.94
20 May						
0 m	1.01	0.05	1.04	0.24	24.53	16.57
4 m	4.46	0.16	0.79	0.91	13.43	34.76
ice	0.76	0.06	2.66	0.46	20.56	14.05

16-18°00) was detected at the surface, which resulted from mixing with fresh water from the Sagavanirktok River, flowing into the sound *ca.* 10 km to the south. The sea ice had not started to melt. Salinities from ice cores were **lower** than surface water values, probably because of dilution from melting ice in the core samples.

Phosphate, nitrate, and nitrite concentrations were highest in the water column at 4 m. Silicate concentrations were highest at 0 m, which may have been due to the influence of the Sagavanirktok River, as silicate content of rivers draining into the Beaufort Sea is known to be high (Hufford 1974b). The concentration of ammonia in the ice, *ca.* 2-3  $\mu\text{g-at l}^{-1}$ , was approximately twice the surface water level, and probably resulted from excretion by fauna associated with the bottom of the ice, reflecting the relatively high biological activity of this zone.

### 3. Zooplankton

Forty-nine categories, including 37 species and 12 other categories, including larval stages or where identification was made to genus or other higher taxonomic level, were identified in zooplankton samples collected in Nov 1978, Mar and May 1979 in Stefansson Sound (Table 5). Relative abundance and distribution through time are given in Table 6.

Copepods were the most abundant organisms collected in Nov 1978. *Pseudocalanus elongatus* was the dominant species. It was present as stages III, IV, V, and VI, and both males and females were present. Stage II copepodids were found once. *Pseudocalanus major* was also abundant with stages II, III, IV, V, and VI and both males and females being present. *Derjuginia tolli* was present as stages IV females, V mostly females, and VI males and females, while *Acartia longiremis* was present as stage VI males and females. Other copepods were present in small numbers. The only cyclopoid copepod was *Oithona similis* with abundant adult females being found twice.

Other animals present included *Mysis* spp., the amphipods *Anonyx nugar*, *Boeckosimus plautus*, *Onisimus litoralis*, and *Orchomenella pinguis*, and the chaetognath *Sagitta elegans*. None of these animals was very abundant.

In Mar 1979, *Pseudocalanus elongatus* was still the dominant copepod with stages I, II, III, IV, V, and VI all being present. Other copepods included *Calanus glacialis* stages I, II, and III; *Microcalanus pygmaeus* stages III, IV males and females, V males and females, and VI only females; *Pseudocalanus major* as stages I and III, and IV and V males and females; *Eurytemora richingsi* stages III, IV mostly females, and V females; *Metridia lucens* stages I, II, and III; and many unidentified nauplii. The presence of early life history stages may indicate some reproduction occurred during the winter. The cyclopoid *Oithona similis* as stages II, III, IV, and V females and VI males and females and *Oncaea borealis* as adult males and females were present usually in low numbers.

Also in March, a few hydrozoans were present along with some polychaete larvae. A cladoceran, *Eubosmina longispina*, was found once and ostracods were also found once. A few amphipods were present and a few *Sagitta elegans*.

Table 5. Zooplankton species from samples collected in Stefansson Sound, Nov 1978, Mar and May 1979.

---

Cnidaria - Hydrozoa

*Halitholus cirratus* Hartlaub

*Sarsia tubulosa* (M. Sars)

Unidentified Hydrozoa

Ctenophora

*Pleurobrachia pileus* (O. F. Müller)

Nematoda - unidentified species

Annelida

Polychaeta - unidentified larvae

Arthropoda - Crustacea

Cladocera

*Eubosmina longispina* (Leydig)

Ostracoda - unidentified species

Cirripedia

*Balanus* sp. nauplii

Unidentified larvae

Unidentified parasitic larvae

Isopoda - unidentified epicaridean parasite

Copepoda

Calanoida

*Calanus glacialis* Jaschnov

*Calanus hyperboreus* Krøyer

*Microcalanus pygmaeus* (G. O. Sars)

*Pseudocalanus elongatus* (Boeck)

*Pseudocalanus major* G. O. Sars

*Derjuginia tolli* (Linko)

*Eurytemora richingsi* Heron and Damkaer

*Metridia longa* (Lubbock)

*Metridia lucens* Boeck

*Limnocalanus macrurus* G. O. Sars

*Acartia longiremis* (Lilljeborg)

Cyclopoida

*Oithona similis* Claus

*Cyclopina gracilis* (Claus)

*Cyclopina* sp. A

*Cyclopina* sp. B

*Cyclopinodes* sp. A

*Oncaea borealis* G. O. Sars

Harpacticoida

*Pseudobradia minor* (T. & A. Scott)

*Harpacticus superflexus* Willey

*Tisbe furcata* (Baird)

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Table 5. (cent. )

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**Mysidacea**  
*Mysis litoralis* (Banner)  
*Mysis oculata* (Fabricius)  
*Mysis relicta* (Lovén)

**Amphipoda**  
**Gammaridea**  
*Atylus carinatus* (Fabricius)  
*Weyprechtia pinguis* (Krøyer)  
*Anonyx nugax* (Phipps)  
*Acanthostephea behringiensis* (Lockington)  
*Boeckosimus plautus* (Krøyer)  
*Onisimus glacialis* Sars  
*Onisimus litoralis* (Krøyer)  
*Orchomenella pinguis* Boeck  
*Lagunogammarus wilkitzkii* (Birula)

**Hyperiidia**  
*Parathemisto libellula* (Liechtenstein)

**Euphausiacea**  
*Thysanoessa raschii* (M. Sars)  
Unidentified calyptopis

**Chaetognatha**  
*Sagitta elegans* Verrill

**Chordata - Larvacea**  
*Fritillaria borealis* Lohmann

---

Table 6a. Relative abundance and distribution through time of zooplankton taxa other than copepods collected in Stefannson Sound, 1978-1979. Nov 1978 samples collected with a 0.75 m ring net, mesh size 308  $\mu\text{m}$ ; Nar and May 1979 samples collected with a 0.5 m ring net, mesh size 216  $\mu\text{m}$ . Where no symbol is present, no animals were found. P = < 1000; A = 1001 - 5000; O = 5001-10000; X = > 10001.

Taxon	8	8	9	9	10	10	Nov 11	11	12	12	13	13	14	14	14	
<b>Cnidaria</b> - Hydrozoa																
<i>Aeginopsis laurentii</i>																
<i>Euphysa flammea</i>																
<i>Halitholus cirratus</i>																
<i>Sarsia tubulosa</i>																
Unidentified Hydrozoa																
<b>Ctenophora</b>																
<i>Pleurobrachia pileus</i>																
<b>Polychaeta</b> - unidentified larvae																
<b>Arthropoda</b>																
<b>Cladocera</b>																
<i>Eubosmina longispina</i>																
<b>Ostracoda</b> - unidentified																
<b>Cirripedia</b>																
<i>Balanus</i> sp. nauplii																
Unidentified larvae																
Unidentified parasitic larvae																
Isopoda																
Unidentified epicaridean parasite																
<b>Mysidacea</b>																
<i>Mysis litoralis</i>						P			P		P				P	
<i>Mysis oculata</i>								P								P
<i>Mysis relicts</i>			P													A
Unidentified species	P															P

Table 6a. (cent.)

Taxon	8	8	9	9	10	10	11	Nov 11	12	12	13	13	14	14	14
<b>Amphipoda</b>															
<b>Gammaridea</b>															
<i>Atylus carinatus</i>				P							P	P			
<i>Weyprechtia pinguis</i>															
<i>Lagunogammarus wilkitzkii</i>															
<i>Anonyx nugax</i>			P	P				P							
<i>Acanthostepheia behringiensis</i>		P													
<i>Boeckosimus plautus</i>			P	Δ		P	A	P	P	P			A		
<i>Onisimus glacialis</i>															
<i>Onisimus litoralis</i>								P			A	A			
<i>Oremonella pinguis</i>									P		P	P			
Unidentified species															P
<b>Hyperidae</b>															
<i>Parathemisto libellula</i>		P													
<b>Euphausiacea</b>															
<i>Thysanoessa raschii</i>															
Unidentified calyptopids															
<b>Chaetognatha</b>															
<i>Sagitta elegans</i>	P				P						P	P		A	
Unidentified animals	P					P									P
Unidentified invertebrate eggs															O

Table 6a. (cont.)

Taxon	Date													
	14	Nov 15	16	16	16	12	Mar 12	13	13	14	14	15	16	May 16 16
<b>Cnidaria - Hydrozoa</b>														
<i>Aeginopsis laurentii</i>														
<i>Euphysa flammea</i>														
<i>Halitholus cirratus</i>					P	P								Δ
<i>Sarsia tubulosa</i>						P								
Unidentified Hydrozoa							P							
<b>Ctenophora</b>														
<i>Pleurobrachia pileus</i>		P												
<b>Polychaeta - unidentified</b>							P			P				
<b>Arthropods</b>														
<b>Cladocera</b>														
<i>Eubosmina longispina</i>							P							
Ostracoda - unidentified							P							
<b>Cirripedia</b>														
<i>Balanus</i> sp. nauplii					A									
Unidentified larvae														
Unidentified parasitic larvae														P
<b>Isopoda</b>														
Unidentified epicaridean parasite														P
<b>Mysidacea</b>														
<i>Mysis litoralis</i>		P	A											
<i>Mysis oculata</i>														
<i>Mysis relicta</i>														
Unidentified species														

Table 6a, (cont.)

Taxon	14	15	Nov 16	16	16	12	12	13	Mar 13	14	14	15	16	16	May 16
<b>Amphipoda</b>															
<b>Gammaridea</b>															
<i>Atylus carinatus</i>															
<i>Weyprechtia pinguis</i>		P													
<i>Lagunogammarus wilkitzki</i>			P												
<i>Anonyx nugax</i>			P	P											
<i>Acanthostepheia behringiensis</i>															
<i>Boeckosimus plautus</i>			Δ	P					P						
<i>Onisimus glacialis</i>									P						
<i>Onisimus litoralis</i>										P	P				
<i>Orchomenella pinguis</i>			P	P											
Unidentified species									P						
Hyperiididae															
<i>Parathemisto libellula</i>															
<b>Euphausiacea</b>															
<i>Thysanoessa raschii</i>			P												
Unidentified calyptopids															
<b>Chaetognatha</b>															
<i>Sagitta elegans</i>			P	Δ						P					
Unidentified animals															
Unidentified invertebrate eggs			O												

Table 6b. Relative abundance and distribution through time of copepods collected in Stefansson Sound, 1978-1979. Nov 1978 samples collected with a 0.75 m ring net, mesh size 308  $\mu\text{m}$ ; Mar and May 1979 samples collected with a 0.5 m ring net, mesh size 216  $\mu\text{m}$ . Where no symbol is present, no animals were found. P = < 1000; A = 1001 - 5000; O = 5001 - 10000; X = 10001 - 20000; ● = 20001 - 50000; + = > 50001; m = male; f = female.

Taxon	8	8	9	9	10	10	11	Nov 11	12	12	13	13	14	14	14
<b>Calanoida</b>															
<i>Calanus glacialis</i> VI m															
f															
III m															x
f	●														
II															x
I															
<i>Calanus hyperboreus</i> V m															
f	●														
<i>Microcalanus pygmaeus</i> VI m															
f															x
V m															
f															
IV m															
f															
111 m															
f															
<i>Pseudocalanus elongatus</i> VI m					●	●		●		●	●	x		+	
f	●	●	+	+	+	+	+	+	+	+	+	+	+	+	+
V m	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
f	+	+	+	+	+	+	+	+	●	+	+	+	+	+	●
IV m	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
f	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
111 m															
f	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
11	●														
I															

Table 6b. (cont.)

Taxon	Nov														
	8	8	9	9	10	10	11	11	12	12	13	13	14	14	14
<i>Pseudocalanus major</i> VI m															
f	•			•	•						•	+			
V m	+				+							+			e
f	•			•	+			•				e			•
IV m	+				+									+	
f	+				+									+	
III m															
f	+				+										
11	•														
I															
<i>Derjuginiatolli</i> VI m	•					•		•	•					+	
f	•						•							+	x
V m	•					•	•							+	x
f						•	•			•					
IV m															
f	•								•						
<i>Eurytemora richingsi</i> V m															
f															
IV m															
f	•														
111 m															
f															
<i>Metridia lucens</i> VI m															
f				•											
III m															
f															
11															
I															
<i>Limnocalanus macrurus</i> VI m	•														
f	•														
<i>Acartia longiremis</i> VI m															
f		x		•	•		•	•		•		x		•	x
				•	•		•			•		x		•	

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Table 6b. (cent.)

Taxon		8	8	9	9	10	10	11	Nov		12	12	13	13	14	14	14
									11	11							
Unidentified nauplii																	
<b>Cyclopoida</b>																	
<i>Oithona similis</i>	VI m																
	f						●										
	V m																
	f													x			
	IV m																
	f																
	111 m																
	f																
<i>Cyclopina gracilis</i>	VI m																
	f																
<i>Cyclopina</i> sp. A	VI m																
	f																
<i>Cyclopina</i> sp. B	VI m																
	f																
<i>Cyclopinodes</i> sp. A	VI m																
	f																
<i>Oncaea borealis</i>	VI m																
	f																
<b>Harpacticoida</b>																	
<i>Pseudobradya minor</i>	juveniles																
<i>Harpacticus superflexus</i>	VI m																
	f																
	juveniles																
<i>Tisbe furcata</i>	VI m																
	f																

Table 6b. (cont.)

Taxon	Nov					Mar				May					
	14	15	16	16	16	12	12	13	13	14	14	15	16	16	16
<b>Calanoida</b>															
<i>Calanus glacialis</i>															
VI m															
f															
III m															
f												Δ			
II															
I												P		P	
<i>Calanus hyperboreus</i>															
V m															
f															
<i>Microcalanus pygmaeus</i>															
VI m						P	P	P				P	P	P	
f															
V m															
f						P									
IV m												P		P	P
f						P		P						P	Δ
III m														P	
f										Δ		P	P		P
<i>elongatus</i>											P				Δ
VI m	X		●	x							P				Δ
f	+		+	+	+							P			Δ
V m	+	+	+	+	+	Δ	○				○	Δ	Δ		○
f	+	+	+	+	+	P					P	Δ	P	P	Δ
IV m	+	+	+	+	+	x	x	○	P	x	●	○	x	○	Δ
f	+	+	+	+	+	●	●	○	○	●	+	○	x	○	○
III m		+		+											
f	+	+	+	+	+	+	+	●	P	●	+	●	●		Δ
II						○	○	○		○	○	P	Δ	Δ	
I						Δ	Δ	Δ		Δ	Δ	P		P	Δ

Table 6b. (cont.)

Taxon	Date																	
	14	15	Nov		16	16	12	12	13	13	Mar		14	15	16	16	May	
<i>Pseudocalanus major</i>	VI m					x												
	f																	
	V m	●								P							O	
	f	+	●	●		x											P	
	IV m									Δ								
	f	x								Δ								
III m										P								
f																		
11																		
I										P								
<i>Derjuginia tolli</i>	VI m																	
	f	●																
V m																		
f																		
IV m																		
f																		
<i>Eurytemora richingsi</i>	V m												P					
	f																	
	IV m																P	
f								P				P				Δ		
111 m																	P	
f												P						
<i>Metridia lucens</i>	VI m																	
	f																	
	III m																	
	f								P			P						
11									Δ		P					P		
I											P							
<i>Limnocalanus macrurus</i>	VI m				x													
	f																	
<i>Acartia longiremis</i>	VI m					x												
	f		●			x	x										P	
																	Δ	
																	P	

Table 6b. (cont.)

Taxon	14	15	Nov		16	16	12	12	13	Mar		14	14	15	16	16	May	
			16	16						13	13						16	16
Unidentified nauplii						0	0	0	0	x	x	o	Δ	o			e	
<b>Cyclopoida</b>																		
<i>Oithona similis</i> VI m											P	P	P				A	
f											A	Δ	A				●	
V m											x	x	o				x	
f																		
IV m											x	0	0				Δ	
f																		
III m																		
f											P		P				A	
<i>Cyclopina gracilis</i> VI m																	Δ	
f																	P	
<i>Cyclopina</i> sp. A VI m																	A	
f																		
<i>Cyclopina</i> sp. B VI m																		
f																		
<i>Cyclopinodes</i> sp. A VI m																		
f																		
<i>Oncaea borealis</i> VI m													P	A				
f											A	P						
<b>Harpacticoida</b>																		
<i>Pseudobradya minor</i> juveniles																		●
<i>Harpacticus superflexus</i> VI m																		A
f																		P
juveniles																		O
<i>Tisbe furcata</i> VI m																		P
f																		

Only one sample was collected in mid-May in conjunction with another project. *Pseudocalanus elongatus* was still the most common animal with stages I, III, IV, V, and VI males and females being present. A few *Microcalanus pygmaeus* stages III and IV were present along with stage VI *Acartia longiremis* males and females. The cyclopoids *Oithona similis* as stages III, IV, and V females and stage VI males and females; and *Cyclopina gracilis*, *Cyclopina* spp. and *Cyclopinodes* sp. stage VI's were also present. The harpacticoid, *Harpacticus superflexus*, was relatively common as juveniles and adult males and females.

## B. Narwhal Island, spring 1980

### 1. Primary productivity

During April, ice algal productivity was low,  $< 0.2 \text{ mg C m}^{-2} \text{ hr}^{-1}$  (Table 7, Fig. 3). Productivity began to increase during the first week in May when submarine light levels increased (Fig. 3), and reached a peak of  $0.8 \text{ mg C m}^{-2} \text{ hr}^{-1}$  on 8 May. A week of stormy weather with fog and blowing snow followed. When sampling resumed, submarine light had dropped to one-half the previous level and productivity to ca.  $0.1 \text{ mg C m}^{-2} \text{ hr}^{-1}$ . Presumably in response to increasing light levels, productivity increased to a high of  $2.7 \text{ mg C m}^{-2} \text{ hr}^{-1}$  on 29 May. On this date, snow was completely gone from the surface of the ice and overflow from the Sagavanirktok River was first noticed by the divers. By the next sampling day, the soft bottom layer of ice containing the ice algae had begun to dissociate from the ice and formed a slush layer loosely associated with the undersurface of the ice. Small pieces of this slush layer clouded the water column. Productivity dropped during the following week, but increased to  $2.6 \text{ mg C m}^{-2} \text{ hr}^{-1}$  on 7 Jun, comparable to the previous high level. By 11 Jun, the underside of the ice had begun to melt and erode, and the algal layer was no longer evident.

Surface and 7 m water column productivity values were integrated to give productivity on a  $\text{m}^2$  basis to allow comparison with ice algal and benthic microalgal communities (Fig. 3). Surface and 7 m water column productivity are also given on a  $\text{m}^3$  basis (Fig. 4a).

Water column productivity was low,  $< 0.2 \text{ mg C m}^{-3} \text{ hr}^{-1}$ , during April and the first half of May, but increased during late May and early June. Two productivity peaks were evident, 22 May and 7 Jun, which coincided with periods of high ice algal productivity. The highest productivity,  $0.4 \text{ mg C m}^{-3} \text{ hr}^{-1}$ , occurred at 0 m on 7 Jun and probably resulted from the ice algal layer that was rapidly disintegrating into the water column. Productivity occurred primarily at 0 m, with productivity at 7 m near the limit of detection throughout most of the study.

Benthic productivity remained near or below the limit of detection, ca.  $0.01 \text{ mg C m}^{-2} \text{ hr}^{-1}$ , throughout the study. Light reaching the benthos was only ca. 0.2% of surface levels, and probably limited growth. Although light levels in the ice increased as the snow melted, shading from the growing ice algal layer prevented an increase in light at depth.

Daily and total primary productivity contributed by the ice algae,

Table 7. Summary of data from Narwhal Island, spring 1980. Where no number is present, no sample was taken. 0 and 7 m productivity and plant pigment data are in  $\text{mg m}^{-3}$ . \* indicates questionable data; + = based on 24 hr incubation; - = dark uptake greater than light.

Sta	Date	Depth (m)	Light (% Sfc)	Chl a ( $\text{mg m}^{-2}$ )	Phaeo ( $\text{mg m}^{-2}$ )	Prim Prod ( $\text{mg C m}^{-2} \text{hr}^{-1}$ )	Salinity ( $\text{‰}$ )	$\text{NO}_3$	$\text{NO}_2$	$\text{NH}_3$ ( $\mu\text{g-at } \ell^{-1}$ )	$\text{PO}_4$	$\text{SiO}_4$
1	10 Apr	ice		1.2	0.1	0.14	34.503	10.6	0.13		1.08	25
		0		0.1	0.1	0.01	35.213	10.1	0.07	0.01	1.27	22
		7		0.1	0.0		35.712	10.6	0.10	0.00	1.30	23
		sed										
2	12	ice										
		0		0.4	0.0	0.01 <sup>+</sup>	34.962	10.3	0.08	0.18	1.34	23
		7		0.1	0.0	0.01 <sup>+</sup>	35.312	10.3	0.08	0.00	1.25	23
		sed										
3	14	ice				0.05	33.731	10.3	0.10	0.75	1.08	24
		0		0.1	0.0	0.01	34.772	10.3	0.07	0.00	1.43	23
		7		0.0	0.0		35.077	10.5	0.08	0.00	1.29	23
		sed		0.7	1.5							
4	17	ice		0.4	0.1	0.03	33.825	10.6	0.10	1.12	4.06*	23
		0		0.1	0.0	0.04	34.911	10.5	0.06	0.01	1.33	23
		7		0.0	0.0		35.264	10.6	0.09	0.00	1.32	24
		sed		13.3	5.0	< 0.01						
5	19	ice		0.4	0.0	0.08	34.020	10.3	0.07	0.59	10.50*	24
		0		0.1	0.1	0.05	34.745	10.2	0.05	0.10	3.31*	23
		7		0.0	0.0	0.01	35.528	10.8	0.09	0.00	4.55*	24
		sed		0.9	1.6	< 0.01						
6	24	ice		2.4	0.2	0.07	32.582	9.9	0.11	0.69	1.17	23
		0		0.1	0.0	0.04	34.240	10.2	0.04	0.05	1.63	23
		7		0.1	0.0	0.01	35.312	11.0	0.09	0.00	1.49	24
		sed		6.8	3.1	< 0.01						

Table 7. (cent. )

Sta	Date	Depth (m)	Light (% Sfc)	Chl a (mg m <sup>-2</sup> )	Phaeo (mg m <sup>-2</sup> )	Prim Prod (mg C m <sup>-2</sup> hr <sup>-1</sup> )	Salinity (‰)	NO <sub>3</sub>	NO <sub>2</sub>	NH <sub>3</sub> (μg-at ℓ <sup>-1</sup> )	PO <sub>4</sub>	sio4
244	7 28	ice				0.01 <sup>+</sup>						
		o	0.34			0.01 <sup>+</sup>						
		7										
		sed										
	8 29	ice	0.06	0.0	0.0	0.02	31.646	10.3	0.13	0.77	1.03	24
		o	0.02	0.2	0.1	0.06	34.332	10.3	0.05	0.02	11.82*	24
		7	0.08	0.1	0.1		35.176	10.8	0.08	0.00	3.60*	24
		sed		1.4	1.5							
	9 2 May	ice	0.65	8.3	1.2	0.22	33.069	9.0	0.23	0.54	4.40*	20
		o	0.52	0.2	0.1	0.01	34.381	10.0	0.07	0.14	15.63*	24
		7	0.21	0.1	0.0		35.320	10.7	0.08	0.14	25.26*	26
		sed		9.5	5.8							
10 5	ice	1.37	4.3	0.3	0.35	33.046	9.0	0.17	0.74	4.94*	21	
	o	0.87	0.3	0.1	0.01	34.436	9.7	0.06	0.06	1.49	23	
	7	0.20	0.3	0.2		35.593	10.8	0.08	0.01	1.39	24	
	sed		8.3	4.2	0.01							
11 6	ice	0.89			0.33 <sup>+</sup>							
	o	0.84			0.04 <sup>+</sup>							
	7	0.18			0.01 <sup>+</sup>							
	sed				< 0.01 <sup>+</sup>							
12 8	ice	0.81	2.2	0.3	0.77	32.632	9.6	0.28	0.76	1.13	23	
	o	0.49	0.2	0.2	0.05	34.571	9.6	0.08	0.09	1.36	23	
	7	0.24	0.0	0.0		35.707	11.0	0.07	0.08	1.49	24	
	sed		1.4	1.8	0.02							



Table 7. (cent. )

Sta	Date	Depth (m)	Light (% sfc)	Chl a (mg m <sup>-2</sup> )	Phaeo (mg m <sup>-2</sup> )	Prim Prod (mg Cm-z hr <sup>-1</sup> )	Salinity (‰)	NO <sub>3</sub>	NO <sub>2</sub> (μg-at l <sup>-1</sup> )	NH <sub>3</sub>	PO <sub>4</sub>	SiO <sub>4</sub>
246	19 26	ice	0.87	13.5	1.5	0.38	30.046	16.6	0.20	1.52	1.89	22
		o	0.36	0.8	0.2	0.09	33.595	8.9	0.07	0.00	4.36	22
		7	0.20	0.2	0.1		33.877	9.3	0.08	0.00	3.94	23
		sed		6.1	2.9							
	20 29	ice	1.74	12.7	1.6	2.64	32.318	9.6	0.13	0.54	1.46	20
		o	0.81	0.2	0.1	0.06	34.122	9.1	0.09	0.00	1.36	23
		7	0.59	0.1	0.1		34.383	9.5	0.09	0.00	1.40	23
		sed		0.9	0.8	0.02						
	21 31	ice	2.00	26.5	3.2	0.77	32.875	17.4	0.32	1.20	1.53	20
		o	0.94	0.5	0.2	0.04	34.208	9.1	0.09	0.03	1.41	23
		7	0.27	0.1	0.1		34.345	9.4	0.09	0.00	1.29	23
		sed		16.5	6.0	< 0.01						
22 2 Jun	ice	1.86	20.4	3.4	0.36	31.516	18.0	0.17	0.87	1.68	22	
	o	0.50	0.3	0.2	0.05	34.031	8.7	0.09	0.03	1.33	22	
	7	0.19	0.1	0.1	0.03	34.497	9.7	0.09	0.01	1.27	23	
	sed		10.9	5.6	0.02							
23 3 Jun	ice	1.36			0.72 <sup>+</sup>							
	o	0.33			0.02 <sup>+</sup>							
	7	0.18			0.01 <sup>+</sup>							
	sed											
24 5	ice	1.30	12.0	2.0	0.46	31.659	16.1	0.18	1.08	2.28	22	
	o	0.56			0.07	33.662	8.2	0.09	0.11	1.11	21	
	7	0.14	0.2	0.1	0.16	34.781	10.4	0.10	0.07	16.95*	25	
	sed		28.7	6.6	< 0.01							

Table 7. (cent. )

Sta	Date	Sample (m)	Light (% Sfc)	Chl a (mg m <sup>-2</sup> )	Phaeo (mg m <sup>-2</sup> )	Prim Prod (mg C m <sup>-2</sup> hr <sup>-1</sup> )	Salinity (‰)	NO <sub>3</sub>	NO <sub>2</sub>	NH <sub>3</sub> (μg-at l <sup>-1</sup> )	PO <sub>4</sub>	SiO <sub>4</sub>
25	7	ice	4.01	17.2	2.7	2.60	31.207	9.7	0.22	1.85	1.77	22
		0	2.65	0.7	0.7	0.42	32.911	8.0	0.10	0.43	1.38	21
		7	0.33	0.2	0.2		34.725	10.4	0.09	0.00	1.38	24
		sed		17.0	7.9							
26	9	ice	1.83	18.0	2.9	1.69	26.383	7.8	0.21	4.33	1.36	21
		0	0.41	1.0	0.1		28.192	8.1	0.09	0.64	1.27	20
		7	0.24	0.1	0.1		34.541	10.2	0.09	0.00	1.22	23
		sed		4.8	2.7	0.01						
27	11	ice	2.80	0.1	0.0		16.385	7.1	0.09	2.26	2.86	21
		0	1.51	1.4	0.3	0.01	24.086	9.9	0.09	0.64	2.62	23
		7	0.23	0.5	0.1	0.01	33.843	6.8	0.16	0.11	0.88	23
		sed		12.2	6.3							

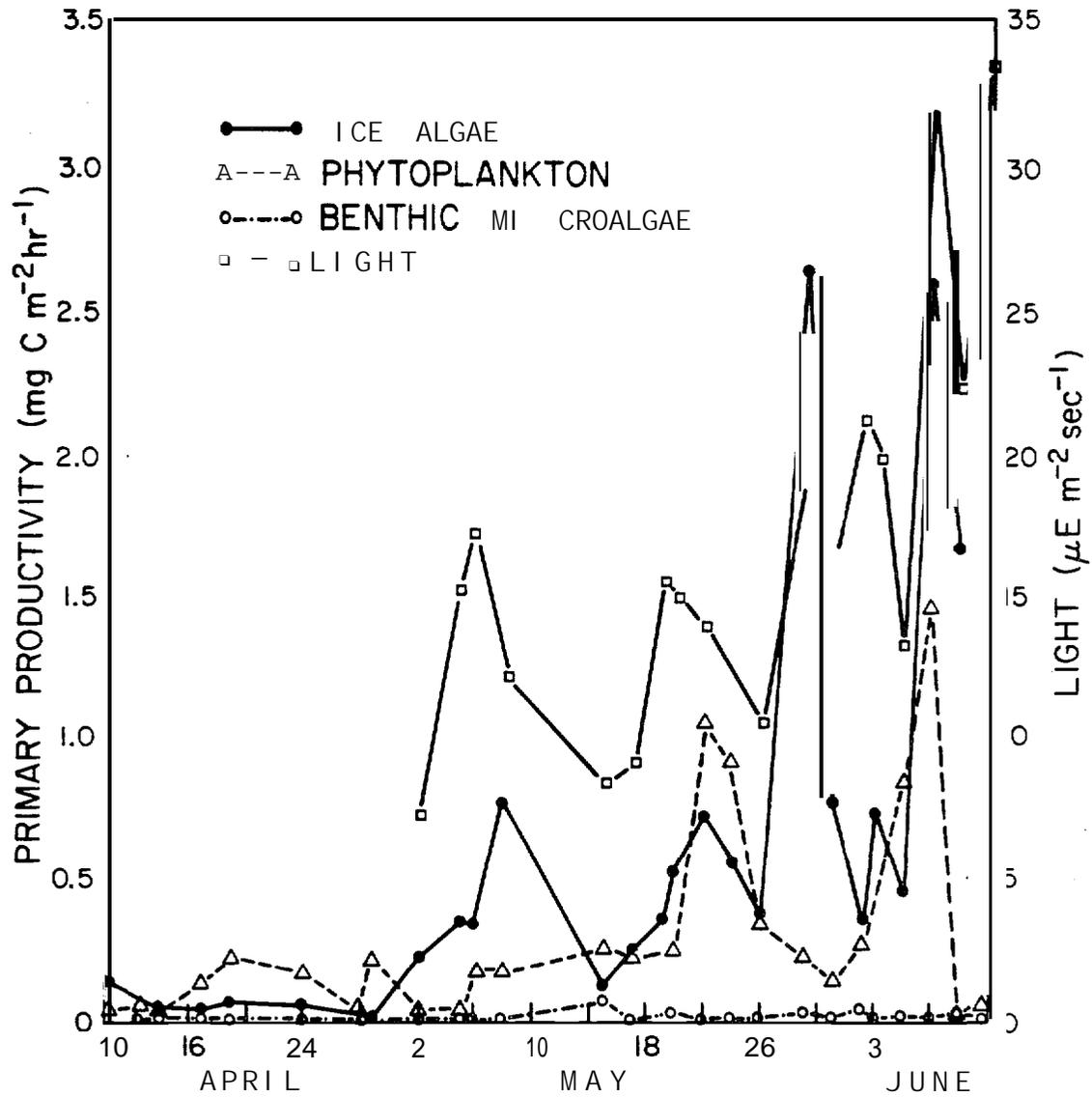


Fig. 3. primary productivity ( $\text{mg C m}^{-2} \text{hr}^{-1}$ ) and incident light intensity ( $\mu\text{E m}^{-2} \text{sec}^{-1}$ ), spring 1980. Productivity of the water column was calculated by integrating productivity at 0 and 7 m.

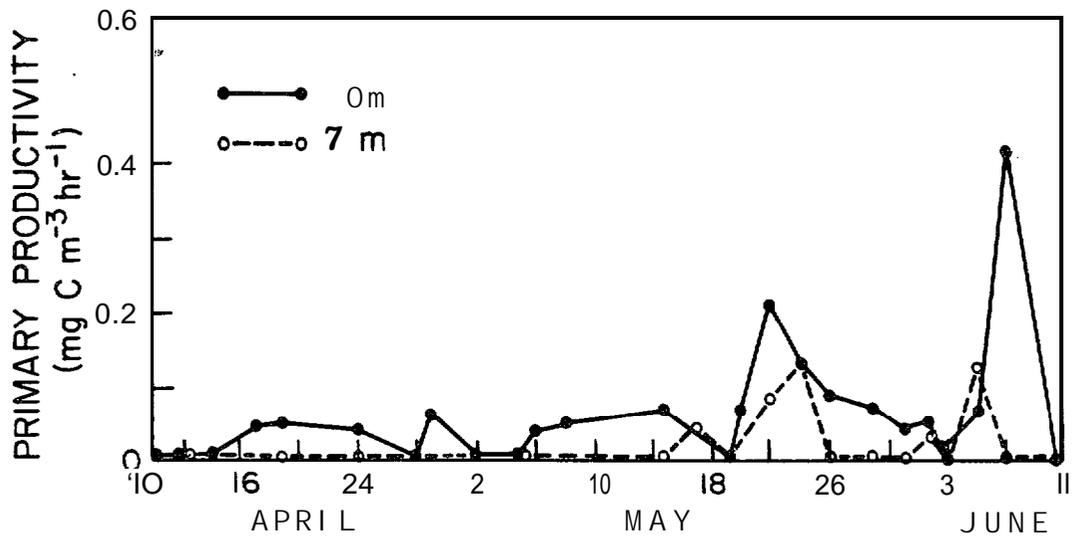


Fig 4a. Primary productivity ( $\text{mg C m}^{-3} \text{ hr}^{-1}$ ) of the water column at 0 and 7 m, spring 1980.

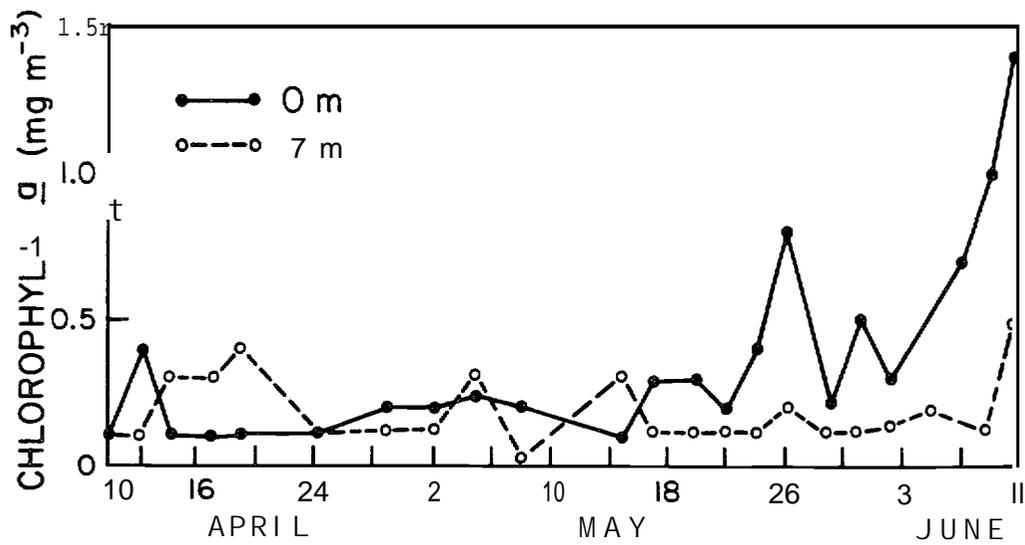


Fig. 4b. Chlorophyll a ( $\text{mg m}^{-3}$ ) of the water column at 0 and 7 m, spring 1980.

phytoplankton, and benthic communities during the study period is summarized in Table 8. Production rates based on 4 and 24 hr incubation periods often differed, but these differences are not considered significant in relation to the high variance found among replicate cores and successive sampling days. During this period the ice algal community contributed  $688 \text{ mg C m}^{-2}$ ; the phytoplankton,  $380 \text{ mg C m}^{-2}$ ; and the benthic community ca.  $12 \text{ mg C m}^{-2}$ . Thus, approximately two-thirds of the primary production occurred in the bottom ice, about one-third occurred in the water column, mainly at the surface, and productivity in the benthos was negligible.

## 2. Plant pigments

Ice algal chlorophyll *a* followed a pattern similar to that shown for primary productivity. Chlorophyll *a* levels were relatively low during April, ea.  $1 \text{ mg m}^{-2}$ , and increased to over  $26 \text{ mg m}^{-2}$  during the second half of May (Fig. 5). Levels remained fairly constant for ca. three weeks and then dropped to near zero at the termination of the bloom on 11 Jun.

Pigment concentrations in the water column remained low throughout most of the study period, rising slightly near the termination of the ice algal bloom. At 7 m, levels were fairly constant, fluctuating between  $< 0.1 \text{ mg m}^{-3}$  to ea.  $0.4 \text{ mg m}^{-3}$  (Fig. 4b). Chlorophyll *a* concentrations at 0 m were about equal to those found at 7 m during April and early May, but increased significantly during the ice algal bloom in late May and early June, reaching a peak of  $1.4 \text{ mg m}^{-3}$  on 11 June. The high surface levels of chlorophyll *a* near the end of the bloom reflect the large quantity of ice algae dropping from the undersurface of the ice into the water column.

Chlorophyll *a* levels in the sediments were comparable to those found on the undersurface of the ice with both communities showing sharp increases during the late May through early June period. During April, however, benthic chlorophyll *a* levels were ea. five times greater than those found in the ice algal community. Fluctuations in chlorophyll *a* levels in the sediments were greater than in the ice, which may be a function of patchiness and differences in sampling technique. Three replicate cores were used to sample the ice algal pigments, but only a single sediment core was taken for benthic pigment determinations.

Because primary productivity in the sediments was negligible, it appears likely that the high chlorophyll is from benthic microalgae remaining in the sediments from the previous season of productivity. This is supported by the high chlorophyll levels in April, when ice algal productivity was low. Subsequent increases in benthic chlorophyll probably resulted from algae falling from the ice, and accumulating in the sediments, as the relative amount of phaeopigments found in the sediments increased during the course of the ice algal bloom.

The relative amount of phaeopigments in the ice was very low compared with the water column and sediments. The ratio  $\Sigma \text{ phaeopigments} : \Sigma \text{ chlorophyll } a$  was 0.13 for the ice; 0.40 at 0 m; 0.55 at 7 m; and 0.49 in the sediments indicating an increase in the relative amount of phaeopigments with depth. As phaeopigments are degradation products of chlorophyll *a*, one would expect this increase with depth because of sinking of fecal

Table 8. Daily and total primary productivity of ice algal, water column, and **benthic** communities. Daily rates were calculated by multiplying the hourly productivity rate by the day length in hours. Total carbon **fixed** was calculated by integrating daily rates over the study period.  
 \* = based on 24 hr incubation period.

Date	Day Length (hr)	Ice	Prim Prod (mg C m <sup>-2</sup> day <sup>-1</sup> )	
			Water	Benthos
10 Apr	15.5	2.2	0.62	
*12	15.8		1.10	0
14	16.4	0.8	0.7	0
17	16.6	0.5	2.3	0
19	16.9	1.4	3.6	0
24	17.8	1.2	3.7	0
*28	18.5	0.01	1.0	0
29	18.7	0.4	3.9	0
2 May	19.3	4.2	0.8	0
5	19.9	7.0	0.8	0.2
* 6	20.2	7.9	4.3	0
8	20.7	15.9	3.6	0.4
15	22.8	2.5	5.7	1.6
*17	24.0	5.8	5.0	0
19	24.0	8.4	0.5	0
20	24.0	12.2	6.0	0
22	24.0	17.0	25.2	0
24	24.0	13.2	21.8	0
26	24.0	9.1	7.7	0
29	24.0	63.4	5.0	0.5
31	24.0	18.5	3.4	0
* 2 Jun	24.0	8.6	6.7	0.5
* 3	24.0	17.3	2.6	0
5	24.0	11.0	19.4	0
7	24.0	62.4	35.3	0
9	24.0	40.6	0	0.2
11	24.0		1.7	0
Total		688	380	12

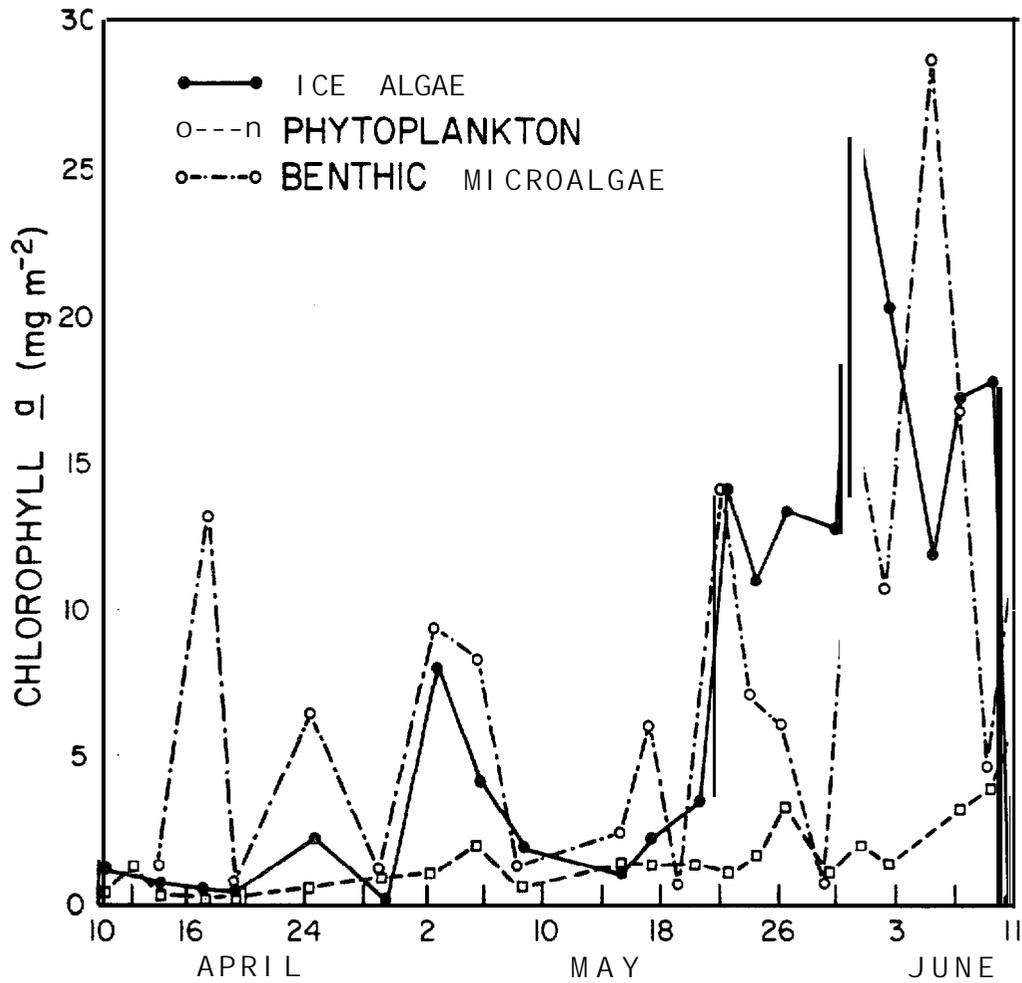


Fig. 5. Chlorophyll *a* (mg m<sup>-2</sup>), spring 1980. Chlorophyll *a* of the ice algae is the average of three replicate cores; chlorophyll *a* of the benthic microalgae is from one core; chlorophyll *a* of the water column was calculated by integrating values from 0 and 7 m.

pellets from grazing herbivores, and from dead algal cells falling from the ice and water column.

On 11 May, a station inside Stefansson Sound in the boulder patch area was sampled for chlorophyll *a* in the bottom ice. The average concentration from two ice cores was 0.24 mg m<sup>-2</sup>, which was low compared with the station outside Narwhal Island. The ice in Stefansson Sound was turbid and **under-ice** light levels were low.

### 3. Standing stock

#### a. Cell numbers

Small, unidentified flagellates, mostly < 6 μm in diameter, accounted for ea. 50% of the cells in the ice algal community (Fig. 6). The remainder of the cells was predominately **pennate** diatoms, with low numbers of centric diatoms, dinoflagellates, and other flagellates. In the water column, **microflagellates** were by far the most numerous organisms, exceeding the concentration of diatoms by an order of magnitude (Fig. 7; Appendix II-2). Although **microflagellates** are considered to be important primary producers in the ocean (Malone 1971), those found in this study did not appear to be photosynthetic. Cell concentrations at the surface remained nearly constant and did not reflect changes in primary productivity or chlorophyll *a*. **Microflagellate** concentrations at 7 m declined by an order of magnitude during the ice algal bloom in late May and early June. **Microflagellates** were not considered further here because they are apparently not photosynthetic.

Ice algal cell concentrations were quite variable, fluctuating between ea. 1 x 10<sup>7</sup> and 1 x 10<sup>9</sup> cells m<sup>-2</sup> during the April to mid-May period (Fig. 8, Appendix II-3). Samples collected after 20 May were far less variable, 6.6 x 10<sup>6</sup> - 1.2 x 10<sup>9</sup> cells m<sup>-2</sup>, suggesting a more patchy distribution earlier in the study, and more uniformity during the height of the bloom. Cell concentrations correlated well with levels of chlorophyll *a*.

The concentration of algal **cells** in the water column was generally at least an order of magnitude lower than that found in either the bottom ice or benthos, averaging ea. 1 x 10<sup>4</sup> cells l<sup>-1</sup> at the surface and 1 x 10<sup>8</sup> cells m<sup>2</sup> for the entire water column. Cell numbers fluctuated greatly during the April to mid-May period, but stabilized during the ice algal bloom period.

Limited resources permitted the enumeration of only a portion of the benthic standing stock samples, but seven cores were analyzed, corresponding to the highest and lowest levels of chlorophyll *a*. Cell numbers correlated well with chlorophyll *a* values and were as high as those found in the ice algal community. Average cell size in the benthic community, however, was considerably smaller than was found in the ice algal community. Cell concentrations were fairly constant, ea. 3 x 10<sup>6</sup> - 3 x 10<sup>9</sup> cells m<sup>-2</sup>, suggesting a more uniform distribution than in the ice algal community.

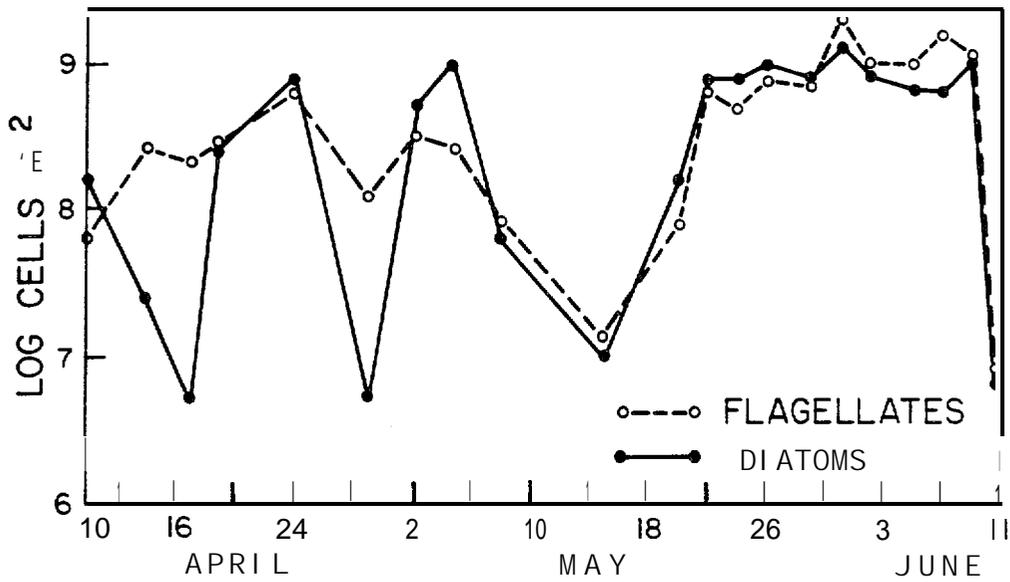


Fig. 6. Concentrations of diatoms and flagellates (log cells m<sup>-2</sup>) in the ice, spring 1980.

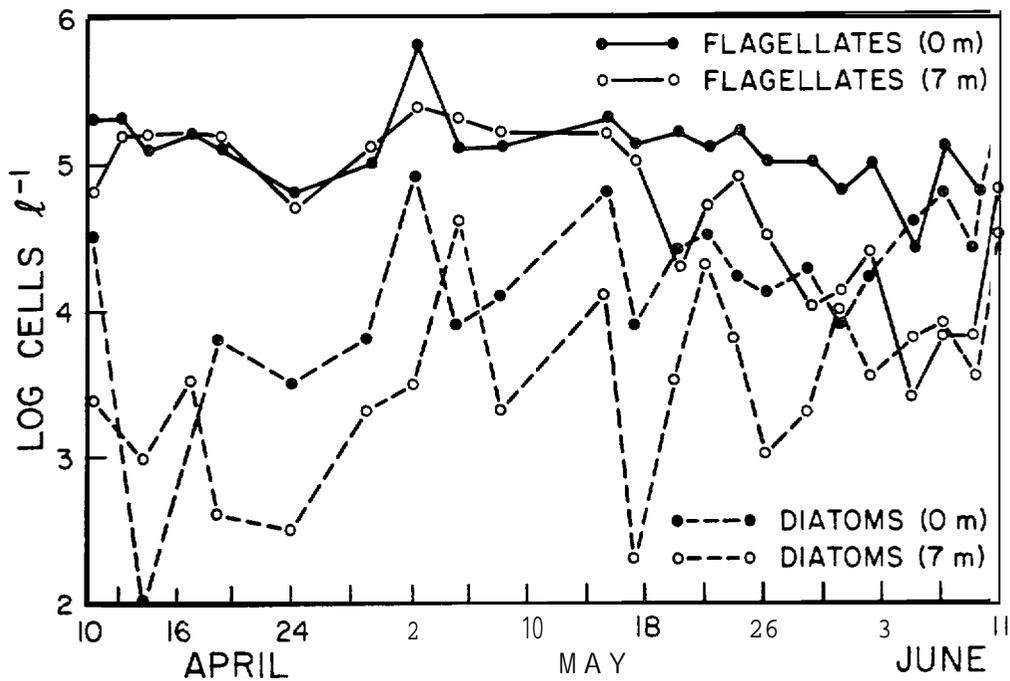


Fig. 7. Concentrations of diatoms and flagellates (log cells l<sup>-1</sup>) in the water column at 0 and 7 m, spring 1980.

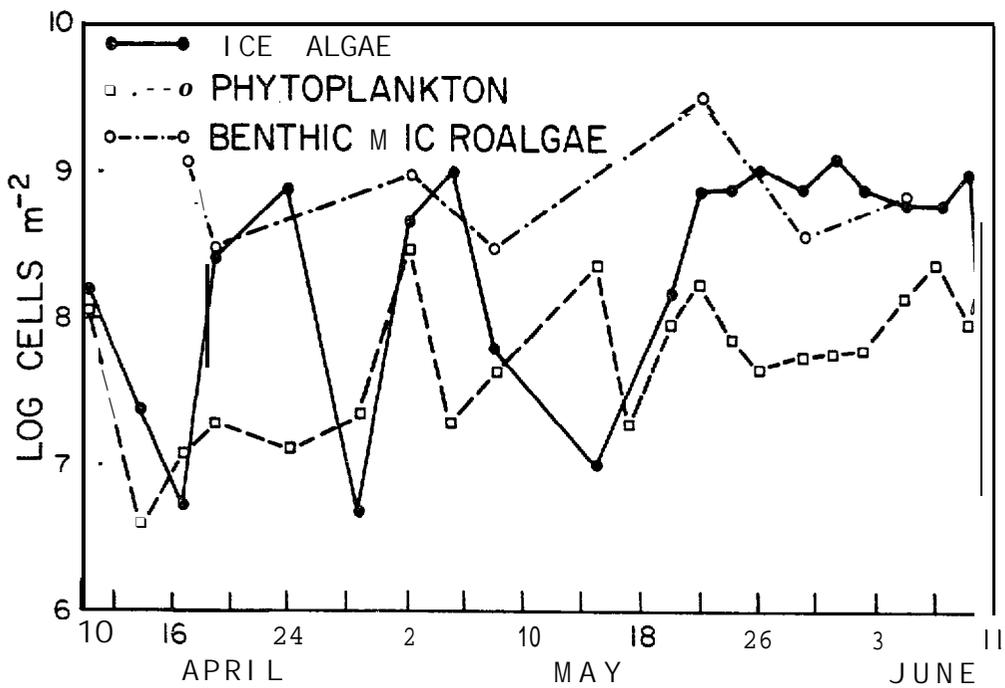


Fig. 8. Concentration of diatoms (log cells m<sup>-2</sup>) in the ice, water column, and benthos, spring 1980.

## b. Species composition

### 1. Ice algae

Seventy-three taxa including 43 species were identified from ice cores. These included 58 species or genera of pennate diatoms, three centric diatoms, four dinoflagellates, and six flagellates (Tables 9-10). The ice algal community was strongly dominated by pennate diatoms, with a single species, *Nitzschia cylindrus*, accounting for an average of 47% of all diatoms counted. Other pennate diatom species that were numerically important included *Amphora ocellata*, *Cylindrotheca closterium*, *Navicula directa*, *N. transitans*, and *Nitzschia frigida*.

Centric diatoms were represented by few species and in low numbers. *Thalassiosira gravida* was the most common, occurring in one-third of the samples. *Chaetoceros septentrionalis* was found once on 9 June, and other small *Chaetoceros* spp., < 10  $\mu\text{m}$ , were present in three samples.

Dinoflagellates were found in low numbers throughout the study and were predominantly unidentified athecate forms. *Peridinium grenlandicum*, *Amphidinium* sp., and *Gymnodinium* sp. were also found. Unidentified flagellates, < 6  $\mu\text{m}$  in diameter, were often dominant organisms in the ice. Other flagellates found were *Dinema litorale*, *Eutreptiella* sp., *Urceolus* sp., *Platymonas* sp., *Cryptomonas* spp., and an unidentified euglenoid.

Changes in community structure and composition were noted during the course of the bloom. During April to mid-May, species diversity was relatively low and was inversely related to cell numbers (Fig. 9). Changes in diversity were due largely to changes in the relative percentage by cell numbers of *Nitzschia cylindrus*. Fluctuation in cell numbers reflect the patchy distribution of the ice algae, suggesting that within patches (high cell numbers) the community was more strongly dominated by *N. cylindrus*. During the second half of May, when chlorophyll a and standing stocks increased precipitously and stabilized at high levels, the diversity of the community began to increase. *Nitzschia cylindrus* became less dominant and cells often appeared unhealthy. Both *N. cylindrus* and another dominant species, *Navicula spicula*, were parasitized by chytridiaceous fungi. Several species became common that had not been identified previously, or that had occurred rarely earlier in the study. These included *Achnanthes taeniata*, *Amphora ocellata*, *Cylindrotheca closterium*, *Navicula directa*, *Nitzschia* sp. A, *Pinnularia quadratarea* var. *kerquelenensis*, *Synedra* sp., and *Thalassiothrix* sp.

A bottom ice sample collected with a SIPRE corer on 9 Nov 1980 by RU 537 contained the same species that made up the spring assemblage. *Nitzschia cylindrus* dominated the community, comprising 92% of the cell numbers.

### 2. Phytoplankton

Fifty-six taxa, including 35 species, were identified in samples from the water column (Tables 11-12). These species were predominantly the same as occurred in the ice, with pennate diatoms being the dominant group. Unidentified flagellates, < 6  $\mu\text{m}$  in diameter, were also abundant. Only five species were identified from the water

Table 9. Microalgae species from ice cores collected off Narwhal Island, spring 1980.

---

Pennate diatoms

*Achnanthes taeniata* Grunow  
*Achnanthes* sp.  
*Amphiprora paludosa* var. *hyperborea* (Grunow) Cleve  
*Amphiprora formosa* Meunier  
*Amphiprora kjellmani* Cleve  
*Amphora laevis* Gregory  
*Amphora ocellata* Donkin cf.  
*Amphora* spp.  
*Cylindrotheca closterium* (Ehrenberg) Reimann & Lewin  
*Diploneis* spp.  
*Eunotia* spp.  
*Fragilaria* spp.  
*Gomphonema exiguum* var. *arctica* Grunow  
*Gomphonema kamtschaticum* Grunow  
*Gyrosigma fasciola* (Ehrenberg) Cleve  
*Gyrosigma spenceri* (W. Smith) Griffith & Henfrey  
*Gyro-Pleurosigma* spp.  
*Liomphora* spp.  
*Navicula bolleana* (Grunow) Cleve cf.  
*Navicula cancellata* Donkin  
*Navicula directa* (W. Smith) Ralfs in Pritchard  
*Navicula kjellmani* Cleve  
*Navicula lyroides* Hendey  
*Navicula maculosa* Donkin  
*Navicula marina* Ralfs  
*Navicula pelagica* Cleve  
*Navicula peregrina* (Ehrenberg) Kützing  
*Navicula peregrina* var. *meniscus* (Schumann) Grunow  
*Navicula spicula* (Hickie) Cleve  
*Navicula transitans* var. *derasa* (Grunow) Cleve  
*Navicula transitans* var. *erosa* (Cleve) Cleve  
*Navicula trigonocephala* Cleve  
*Navicula valida* var. *minuta* Cleve  
*Navicula* sp. A,  
*Navicula* sp. B  
*Nitzschia angularis* W. Smith  
*Nitzschia cylindrus* (Grunow) Hasle  
*Nitzschia frigida* Grunow  
*Nitzschia seriata* Cleve  
*Nitzschia sigma* (Kützing) W. Smith cf.  
*Nitzschia sigmoidea* (Nitzsch) W. Smith  
*Nitzschia* sp. A  
*Nitzschia* sp. B  
*Nitzschia* spp.  
*Pinnularia quadratarea* (A. Schmidt) Cleve  
*Pinnularia quadratarea* var. *Antarctica* (M. Peragallo)  
Frenguelli & Orlando  
*Pinnularia quadratarea* var. *interrupts* (Cleve) Cleve

---

Table 9. (cent. )

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*Pinnularia quadratarea* var. *kerguelensis* (Cleve & Grunow)  
Cleve

*Pinnularia quadratarea* var. *theelii* (Cleve) Cleve

*Pseudonitzschia delicatissima* (Cleve) Heiden

*Rhoiconeis* spp.

*Stauroneis quadripedis* (Cleve-Euler) Hendey

*Synedra* spp.

*Thalassiothrix* spp.

*Tropidoneis* spp.

Unidentified pennate diatoms

Centric diatoms

*Chaetoceros septentrionalis* Østrup

*Chaetoceros* spp.

*Thalassiosira gravida* Cleve

Dinoflagellates

*Amphidinium* sp.

*Gymnodinium* spp.

*Peridinium grenlandicum* Woloszyńska

Unidentified dinoflagellates

Flagellates

*Dinema litorale* Skuja

*Eutreptiella* sp.

*Urceolus* sp.

Unidentified euglenoid sp. A

*Platymonas* spp.

Unidentified cryptomonad spp.

---

Table 10. Relative abundance and distribution through time of **microalgae** species from ice cores collected by divers off Narwhal Island, spring 1980, and from one core collected with a **SIPRE** corer in Nov 1980. P = present (< 1%); O = common (1-5%); x = abundant (5-10%); A = dominant (> 10%).

Taxon	Apr						May				
	10	14	17	19	24	29	2	5	8	15	20
Pennate diatoms											
<i>Achnanthes taeniata</i>	P										
<i>Amphiprora alata</i>											
<i>Amphiprora kjellmanii</i>	P	P		P							
<i>Amphiprora paludosa</i> v. <i>hyperborea</i>										P	P
<i>Amphora ocellata</i>									O		x
<i>Cylindrotheca closterium</i>	P		A		P		P	P	P	P	O
<i>Eunotia</i> spp.	P										
<i>Fragilaria</i> sp.											P
<i>Gomphonema exiguum</i> v. <i>arctica</i>	O	O	x	O	O		P	P	P	O	P
<i>Gyrosigma fasciola</i>	P										
<i>Gyro-Pleurosigma</i> spp.	O	P		O	O		P	P	P	P	P
<i>Licmophora</i> spp.	O	x		O	O	o	P	P	P	o	P
<i>Navicula bolleana</i> cf.	P	O		O	P	o	P	P	P	O	
<i>Navicula directa</i>	P						P	O	O	O	O
<i>Navicula kjellmanii</i>											
<i>Navicula maculosa</i>	F										
<i>Navicula marina</i>	P	x	O	P	P		P	P	P	P	P
<i>Navicula pelagica</i>									P		
<i>Navicula spicula</i>	O			O	O	o	A	O	O	O	x
<i>Navicula transitans</i>	P	o		P	P				P	O	O
<i>Navicula trigonocephala</i>	P	O	O	P	P		P	P			P
<i>Navicula valida</i> v. <i>minuta</i>		O			P		P			O	P
<i>Navicula</i> sp. A	P				P						
<i>Nitzschia angularis</i>											
<i>Nitzschia cylindrus</i>	Δ	A	x	A	A	x	A	A	A	A	A
<i>Nitzschia frigida</i>	Δ	o		P	A		A	x	A	x	A
<i>Nitzschia seriata</i>											
<i>Nitzschia sigma</i> cf.											
<i>Nitzschia sigmoidea</i>								P		P	P

Table 10. (cent. )

Taxon	10	14	Apr				24	29	2	5	May		
			17	19	24	29					8	15	20
<i>Nitzschia</i> sp. A											O	O	O
<i>Nitzschia</i> sp. B		O		P	P	O		O	P			P	
<i>Pinnularia quadratarea</i>													
<i>Pinnularia quadratarea</i> v. <i>kerguelensis</i>	P												
<i>Pinnularia quadratarea</i> v. <i>theelii</i>													
<i>Pseudonitzschia delicatissima</i>	P												P
<i>Stauroneis quadripedis</i>												P	P
<i>Synedra utermöhlili</i>													
<i>Synedra</i> sp.													O
<i>Thalassiothrix</i> spp.	P							P					
<i>Tropidoneis</i> sp.													
Unidentified pennate diatoms	A	O	A	A	X	A		A	x	O	A	X	
Centric diatoms													
<i>Chaetoceros gracilis</i>													
<i>Chaetoceros septentrionalis</i>													
<i>Chaetoceros</i> spp.		O	x										
<i>Thalassiosira gravida</i>		P		P	P								
Dinoflagellates													
<i>Amphidinium</i> sp.	P								P		P	P	
<i>Gymnodinium</i> spp.	P												
<i>Peridinium grenlandicum</i>										P			
Unidentified dinoflagellates		P	P	P	P			P	P		P	O	
Flagellates													
<i>Cryptomonad</i> spp.	P		P					P	P				P
<i>Dinema litorale</i>	P				P								
<i>Eutreptiella</i> sp.	P	P	P		P	P		P	P		P	P	
<i>Urceolus</i> sp.													
Unidentified euglenoid sp.												P	P
<i>Platymonas</i> spp.										O	P		
Unidentified flagellates (> 6 µm)	O	Δ	P	O	O	O		A	x	x	x	x	x

Table 10. (cent. )

Taxon	May					Jun					Nov	
	22	24	26	29	31	2	5	7	9	1	1	9
Pennate diatoms												
<i>Achnanthes taeniata</i>	O	O			P	O	x	O	O			P
<i>Amphiprora alata</i>												P
<i>Amphiprora kjellmani</i>												P
<i>Amphiprora paludosa</i> v. <i>hyperborea</i>	P	P	P	P				P				P
<i>Amphora ocellata</i>	P	O	x	x	O	O	P	O	O	O		
<i>Cylindrotheca closterium</i>	O	O	O	x	x	O	x	x	O	O		P
<i>Eunotia</i> spp.										O		
<i>Fragilaria</i> sp.		P			O			O		P		P
<i>Gomphonema exiguum</i> v. <i>arctica</i>	P	P	P	P	P	O	P	P	O	O		P
<i>Gyrosigma fasciola</i>	P	P	P	P	P			P	P			
<i>Gyro-Pleurosigma</i> spp.	O	O	O	P	P	P	P	P	P	P		P
<i>Licmophora</i> spp.	P	P	P	P	P		P	P	O			
<i>Navicula bolleana</i> cf.	P	P			P	O	O	P	O	O		
<i>Navicula directa</i>	O	x	O	O	x	O	A	x	A	O		P
<i>Navicula kjellmani</i>								P				
<i>Navicula maculosa</i>		P		P	P	P	P	P	P			
<i>Navicula marina</i>	P	P	P		P		P	P	P	P		
<i>Navicula pelagica</i>												P
<i>Navicula spicula</i>	O	A	A	A	A	O	x	O	O	O		P
<i>Navicula transitans</i>	O	O	x	A	O	O	O	O	x	x		P
<i>Navicula trigonocephala</i>	O	P	P		P	P	P	P	P			
<i>Navicula valida</i> v. <i>minuta</i>		P	P	P	P	P	P	P	P	O		
<i>Navicula</i> sp. A	P				P							
<i>Nitzschia angularis</i>		P	P	O	P	P						
<i>Nitzschia cylindrus</i>	A	A	A	A	A	A	x	O	x	A		A
<i>Nitzschia frigida</i>	x		O	O	O	A	O	A	A			P
<i>Nitzschia seriata</i>												O
<i>Nitzschia sigma</i> cf.			P		P	P			P			
<i>Nitzschia sigmoidea</i>	P	P	P		P	P			P			

Table 10. (cont.)

Taxon	May					Jun					Nov 9
	22	24	26	29	31	2	5	7	9	11	
<i>Nitzschia</i> sp. A	O	O	P		P	P		P			
<i>Nitzschia</i> sp. B	P		P			P	P				
<i>Pinnularia quadratarea</i>		P	P		P			P	P	P	
<i>Pinnularia quadratarea</i> v. <i>kerguelensis</i>		O	O	O	O	O	P	P	O	O	P
<i>Pinnularia quadratarea</i> v. <i>theelii</i>								P	P		
<i>Pseudonitzschia delicatissima</i>	P	P	P	O	P		P	P	P		O
<i>Stauroneis quadripedis</i>	P	P	P		P						
<i>Synedra utermöhlili</i>											P
<i>Synedra</i> sp.			P	O	O	O	O	O	O		P
<i>Thalassiothrix</i> S <sub>pp.</sub>	O	P	P	P	P		P	P	O	P	
<i>Tropidoneis</i> sp.	P										
Unidentified pennate diatoms	A	x	A	A	A	A	A	A	A	A	P
Centric diatoms											
<i>Chaetoceros gracilis</i>											P
<i>Chaetoceros septentrionalis</i>									P		P
<i>Chaetoceros</i> spp.				P							
<i>Thalassiosira gravida</i>			O	O	O			P		O	P
Dinoflagellates											
<i>Amphidinium</i> S <sub>p.</sub>	P				P	P	P	P		P	
<i>Gymnodinium</i> sp.										P	
<i>Peridinium grenlandicum</i>											
Unidentified dinoflagellates	O		P	P	P	P		P			P
Flagellates											
<i>Cryptomonad</i> spp.		P	P	P							
<i>Dinema litorale</i>	P	P	P	P	P	P	P	P	P		
<i>Eutreptiella</i> sp.	P	P		P	P	P	P			P	
<i>Urceolus</i> Sp.					P						
Unidentified euglenoid sp.	P	P				P	P	P	P		
<i>Platymonas</i> spp.					O	O	P	P	P	P	
Unidentified flagellates (< 6 µm)	A	A	A	A	A	Ax		A	x	A	P

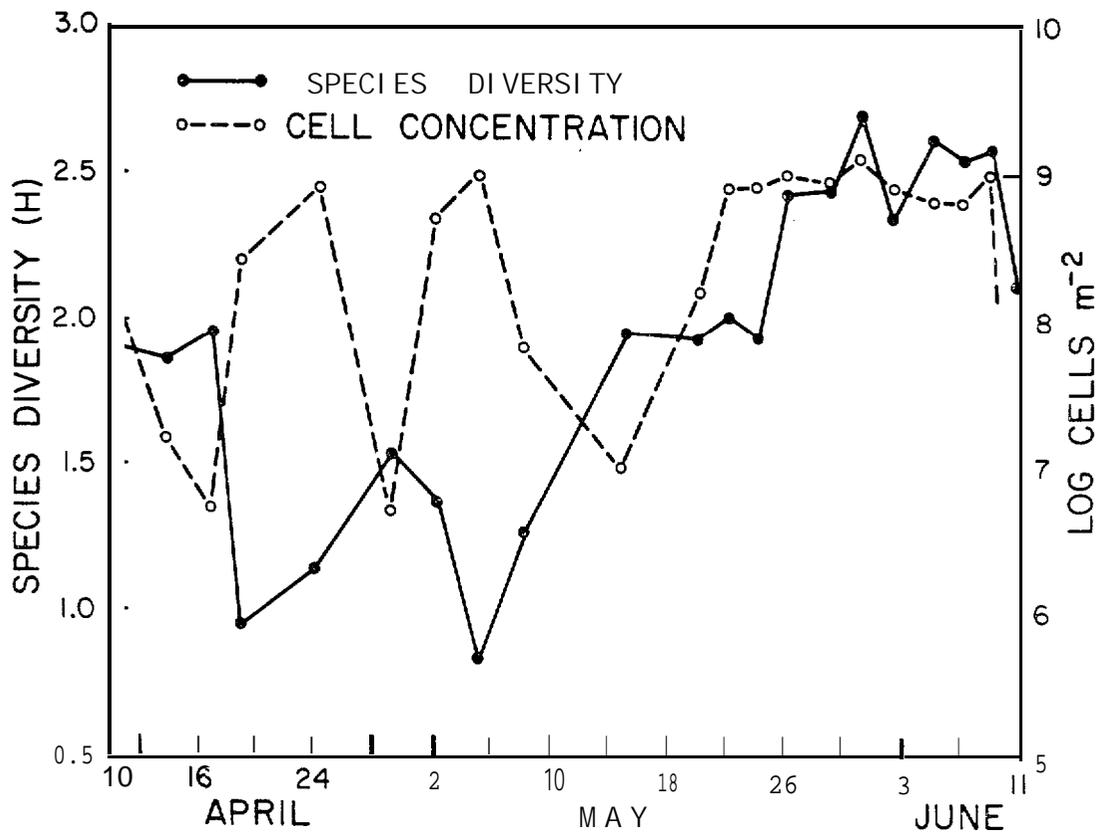


Fig. 9. Shannon-Wiener diversity index and concentration of cells (log cells m<sup>-2</sup>) in the ice community, spring 1980.

Table 11. Phytoplankton species collected off Narwhal Island, spring 1980.

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Pennate diatoms

*Achnanthes taeniata* Grunow  
*Achnanthes* sp.  
*Amphiprora paludosa* var. *hyperborea* (Grunow) Cleve  
*Amphora ocellata* Donkin cf.  
*Amphora* sp.  
*Cylindrotheca closterium* (Ehrenberg) Reimann & Lewin  
*Gomphonema exiguum* var. *arctica* Grunow  
*Gomphonema kantschaticum* Grunow  
*Gyrosigma fasciola* (Ehrenberg) Cleve  
*Gyro-Pleurosigma* spp.  
*Lemphora* sp.  
*Navicula bolleana* (Grunow) Cleve cf.  
*Navicula directa* (W. Smith) Ralfs in Pritchard  
*Navicula kjellmani* Cleve  
*Navicula lyroides* Hendey  
*Navicula maculosa* Donkin  
*Navicula marina* Ralfs  
*Navicula pelagica* Cleve  
*Navicula spicula* (Hickie) Cleve  
*Navicula transitans* var. *derasa* (Grunow) Cleve  
*Navicula trigonocephala* Cleve  
*Navicula valida* var. *minuta* Cleve  
*Navicula* sp. A  
*Nitzschia angularis* W. Smith  
*Nitzschia cylindrus* (Grunow) Hasle  
*Nitzschia frigida* Grunow  
*Nitzschia seriata* Cleve  
*Nitzschia sigma* (Kützing) W. Smith cf.  
*Nitzschia sigmoidea* (Nitzsch) W. Smith  
*Nitzschia* sp. A  
*Nitzschia* sp. B  
*Pinnularia quadratarea* var. *keruelensis* (Cleve & Grunow)  
Cleve  
*Pinnularia quadratarea* var. *theelii* (Cleve) Cleve  
*Pseudonitzschia delicatissima* (Cleve) Heiden  
*Rhoiconeis* sp.  
*Stauroneis quadripedis* (Cleve-Euler) Hendey  
*Stauroneis* sp.  
*Synedra* sp.  
*Thalassiothrix* spp.

Centric diatoms

*Chaetoceros gracilis* Schütt  
*Chaetoceros septentrionalis* Østrup  
*Chaetoceros* spp.  
*Leptocylindrus* sp.  
*Melosira juergensii* Agardh

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Table 11. (cent. )

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*Thalassiosira gravida* Cleve  
*Thalassiosira* spp.

**Dinoflagellates**

*Amphidinium* sp.  
*Dinophysis arctica* Mereschkowsky  
*Excuviaella* sp.  
*Gymnodinium* sp.  
*Peridinium grenlandicum* Woloszyńska

**Flagellates**

*Dinema litorale* Skuja  
*Euglena* sp.  
*Eutreptiella* sp.  
*Platymonas* spp.  
Unidentified flagellates (> 6  $\mu$ m)

Table 12. Relative abundance and distribution through time of phytoplankton species collected at 0 and 7 m off Narwhal Island, spring 1980. P = present (< 1%); O = common (1-5%); x = abundant (5-10%); A = dominant (> 10%).

Taxon	Apr							May						
	10 070	14 7 0	17 7	19 0 7	24 0 7	29 07	2 0 7	5 07	8 07	15 0 7	20 0 7			
Pennate diatoms														
<i>Achnanthes taeniata</i>								P						
<i>Achnanthes</i> sp.				P		P								
<i>Amphiprora paludosa</i> v. <i>hyperborea</i>														
<i>Amphora ocellata</i>					P		P	P	P		P			
<i>Amphora</i> sp.	P									P				
<i>Cylindrotheca closterium</i>				P	P			P	P	P	P			
<i>Gomphonema exiguum</i> v. <i>arctica</i>	P		P	P	P			P		P	P			
<i>Gomphonema kamschaticum</i>									P	P	P			
<i>Gyrosigma fasciola</i>										P				
<i>Gyro-Pleurosigma</i> spp.					P	P		P		P	P			
<i>Licmophora</i> sp.	P				P		P		P	P	P			
<i>Navicula bolleana</i> cf.	P				P		P	P	P	P	P			
<i>Navicula directa</i>	P	P		x	P					P	P			
<i>Navicula kjellmani</i>	P													
<i>Navicula lyroides</i>														
<i>Navicula maculosa</i>				P		P		P	P					
<i>Navicula marina</i>										P				
<i>Navicula pelagica</i>														
<i>Navicula spicula</i>								P	P	P	P			
<i>Navicula transiens</i> v. <i>derasa</i>	P			P	P	P	P		P	P	P			
<i>Navicula trigonocephala</i>								P		P				
<i>Navicula valida</i>														
<i>Navicula</i> sp. A										P	P			
<i>Nitzschia angularis</i>														
<i>Nitzschia cylindrus</i>	P							Δ	P	P	Δ			
<i>Nitzschia frigida</i>						P					A			
<i>Nitzschia seriata</i>			P	P	P					P	P			
											P			
											P A x			

Table 12. (cont.)

Taxon	Apr										May		
	10 07	14 07	17 07	19 07	24 07	29 07	2 07	5 07	8 07	15 07	20 07		
<i>Nitzschia sigma</i> cf.													
<i>Nitzschia sigmoidea</i>													
<i>Nitzschia</i> sp. A													
<i>Nitzschia</i> sp. B				P	P	P	P		P				P
<i>Pinnularia quadratarea</i> v. <i>kerguelensis</i>									P	P		P	P
<i>Pinnularia quadratarea</i> v. <i>theelii</i>				P					P	P			
<i>Pseudonitzschia delicatissima</i>												P	P
<i>Rhoiconeis</i> sp.													
<i>Stauroneis quadripedis</i>				P								P	P
<i>Stauroneis</i> sp.													A
<i>Thalassiothrix</i> spp.							P			P	P	P	P
Unidentified pennate diatoms	P	P	P	PPP	P	P	P	AO	P	P	P	P	P
Centric diatoms													
<i>Chaetoceros gracilis</i>													
<i>Chaetoceros septentrionalis</i>													
<i>Chaetoceros</i> spp.													
<i>Cyclotella</i> sp.													P
<i>Leptocylindrus</i> sp.												P	
<i>Melosira juergensii</i>													P
<i>Thalassiosira gravida</i>													
<i>Thalassiosira</i> spp.			P		P					P	P	P	
Dinoflagellates													
<i>Amphidinium</i> sp.									P		P		A
<i>Dinophysis arctica</i>													
<i>Exuviaella</i> sp.	P												
<i>Gymnodinium</i> sp.										P			
<i>Peridiniwn grenlandicum</i>				P	P							P	
Flagellates													
<i>Dinema litorale</i>													
<i>Euglena</i> sp.													
<i>Eutreptiella</i> sp.				P	P	P	P		P	P	P	P	P
<i>Platymonas</i> spp.												P	
Unidentified flagellates (>6 urn)	x	x	0000	P	P	P	O		O	A	P	X	P
												x	O
													x

Table 12. (cent. )

Taxon	May						Jun					
	22 07	24 07	26 07	29 07	31 07		2 07	5 07	7 07	9 07	11 07	
Pennate diatoms												
<i>Achnanthes taeniata</i>		P P		P								
<i>Achnanthes</i> sp.	P		P					P		P		
<i>Amphiprora paludosa</i> v. <i>hyperborea</i>	P		P									
<i>Amphora ocellata</i>	P P		P		P O		P	P	P P P P P			
<i>Amphora</i> sp.												
<i>Cylindrotheca closterium</i>		P	P	P	P P		P P	O P X X P				
<i>Gomphonema exiguum</i> v. <i>arctica</i>	P	P P										
<i>Gomphonema kantschaticum</i>								P				
<i>Gyrosigma fasciola</i>		P										P
<i>Gyro-Pleurosigma</i> spp.	P P P			P	P		P P P P P P P				P P	
<i>Limnophora</i> sp.	P P P P P		P	P								
<i>Navicula bolleana</i> cf.	P P P P		P P		P			P P	P		P P	
<i>Navicula directa</i>	P P P P			P	P		P P P P P	P	POP	P P	P P	
<i>Navicula kjellmanii</i>												
<i>Navicula lyroides</i>	P											
<i>Navicula maculosa</i>	P											
<i>Navicula marina</i>	P P P											
<i>Navicula pelagica</i>												P P
<i>Navicula spicula</i>	P P	P P P P			P P		P	P P O		P P P P		
<i>Navicula transitans</i> v. <i>derasa</i>	P P	P P	P		P		P	P P P		P P P P		
<i>Navicula trigonocephala</i>	P											P
<i>Navicula valida</i>	P P											P
<i>Navicula</i> sp. A												
<i>Nitzschia angularis</i>	P								P			P
<i>Nitzschia cylindrus</i>	Δ A AP A PO				O		A PxOA	P A P		Δ A		A
<i>Nitzschia frigida</i>	P	P					P	P P O		P P		P
<i>Nitzschia seriata</i>		P P		x				P				



column that were not found in the ice algae samples. Four of these species were centric diatoms, *Chaetoceros gracilis*, *Cyclotella* sp., *Leptocylindrus* sp., and *Melosira juergensii*; and a dinoflagellate, *Exuviella* sp. was also found exclusively in the phytoplankton.

Most of the cells found in the water column appear to have originated in the ice. About 50% of the cells in the samples were empty frustules, and many others appeared to be unhealthy, and were often heavily parasitized. *Nitzschia cylindrus* was present in low numbers during April, but became the dominant diatom species during most of May and early June. This was also the dominant species in the ice algal community. In the water column, however, the cells did not appear to be healthy, and had probably fallen from the ice.

### 3. Benthic microalgae

Cells in seven sediment cores were enumerated and 18 taxa, including 10 species were identified (Tables 13-14). An additional 12 taxa with eight species were identified from empty frustules, but were not represented by living cells. This community consisted almost exclusively of pennate diatoms. The only centric diatom found was a single resting spore of *Chaetoceros* sp. *Dinema litorale* was the only flagellate identified.

Although we were unable to identify the majority of the species present, they were clearly not the same species found in the ice or water column. *Cylindrotheca closterium*, *Navicula cancellata*, *N. directa*, *N. spicula*, *N. transitans* var. *derasa*, *Nitzschia angularis*, and *N. cylindrus* occurred in both the ice and sediments, but comprised a small minority of the cells present in the sediments. *Nitzschia cylindrus*, the dominant species of the ice and water column, was represented by a single pair of cells, that were found near the end of the ice algal bloom and probably had fallen from the ice; they appeared to be unhealthy. Of the taxa represented only by empty frustules, all were members of the ice algal community and probably originated there.

### 4. Zooplankton

Thirty-two categories including 25 species and seven other categories where identification was made to genus or other higher taxonomic rank, were identified (Table 15). Relative abundance and distribution through time are given in Tables 16a-16b.

*Pseudocalanus elongatus* was the most common animal in spring 1980. It was present primarily as stages IV, V, and VI males and females with a few younger stages also being present. Other copepods common during this period included *Acartia longiremis* adult males and females; some adult *Pseudocalanus major*, and *Eurytemora herdmanni*. Adult *Oithona similis* were present in late May and June. Harpacticoid copepods became more abundant in May and June, including *Harpacticussuperflexus* adults and juveniles, and *Helectinosoma neglectum* adults.

Hydrozoans were present throughout the spring, including the meroplanktonic species *Euphysa flammea* and *Halitholus cirratus*, and the holo-

Table 13. Benthic microalgae species collected off Narwhal Island, spring 1980.

---

Pennate diatoms

- Achnanthes* sp.  
*Amphora* sp.  
*Cylindrotheca closterium* (Ehrenberg) Reimann & Lewin  
*Diploneis smithii* (de Brébisson) Cleve  
*Diploneis* sp.  
 \**Gomphonema exiguum* var. *arctica* Grunow  
 \**Gomphonema kantschaticum* Grunow  
 \**Gyrosigma fasciola* (Ehrenberg) Cleve  
 \**Gyro-Pleurosigma* spp.  
*Navicula cancellata* Donkin  
*Navicula cancellata* var. *skaldensis* Van Heurck  
*Navicula directs* (W. Smith) Ralfs in Pritchard  
 \**Navicula gracilis* Kützing  
 \**Navicula peregrina* (Ehrenberg) Kützing  
*Navicula spicula* (Hickie) Cleve  
*Navicula transitans* var. *derasa* (Grunow) Cleve  
*Nitzschia angularis* W. Smith  
*Nitzschia cylindrus* (Grunow) Hasle  
 \**Nitzschia frigida* Grunow  
 \**Pinnularia quadratarea* (A. Schmidt) Cleve  
*Stauroneis* sp.  
*Synedra* spp.  
 Unidentified tube-forming species  
 Unidentified pennate diatoms

Centric diatoms

- \**Chaetoceros* sp.  
*Chaetoceros* sp. resting spore  
 \**Coscinodiscus radiatus* Ehrenberg  
 \**Thalassiosira* sp.

Flagellates

- Dinema litorale* Skuja

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\* empty frustules only

Table 14. Relative abundance and distribution through time of benthic microalgae species from seven sediment cores collected off Narwhal Island, spring 1980. P = present (< 1%); O = common (1-5%); x = abundant (5-10%); A = dominant (> 10%). \* indicates only empty frustules present.

Taxon	Apr						May				
	10	14	17	19	24	29	2	5	8	15	20
Pennate diatoms											
<i>Achnanthes</i> Sp.							x			P	
Amphora sp.											
<i>Cylindrotheca closterium</i>											
<i>Diploneis smithii</i>			x								
<i>Diploneis</i> sp.											
* <i>Gomphonema exiguum</i> v. <i>arctica</i>											
* <i>Gomphonema kantschaticum</i>											
* <i>Gomphonema fragiella</i>											
* <i>Gyro-Pleurosigma</i> spp.											
<i>Navicula cancellata</i>			A	A			A			O	
<i>Navicula cancellata</i> v. <i>skaldensis</i>			P				P				
<i>Navicula directa</i>			P								
* <i>Navicula gracilis</i>											
* <i>Navicula peregrina</i>											
<i>Navicula spicula</i>											
<i>Navicula transitans</i> v. <i>derasa</i>			P	P			P				
<i>Nitzschia angularis</i>				P							
<i>Nitzschia cylindrus</i>											
* <i>Nitzschia frigidula</i>											
* <i>Pinnularia quadratarea</i>											
<i>Stauroneis</i> sp.			P								
<i>Synedra</i> spp.											
Unidentified tube-forming species											
Unidentified pennate diatoms			A	A			A			A	
Centric diatoms											
* <i>Chaetoceros</i> sp.											
<i>Chaetoceros</i> sp. resting spore				P							
* <i>Coscinodiscus radiatus</i>											
* <i>Thalassiosira</i> sp.											
Flagellates											
<i>Dinema litorale</i>										P	

Table 14. (cent.)

Taxon	May					Jun					
	22	24	26	29	31	2	5	7	9	1	1
Pennate diatoms											
<i>Achnanthes</i> sp.	O										
Amphora sp.							P				
<i>Cylindrotheca closterium</i>				P							
<i>Diploneis smithii</i>	O							0			
<i>Diploneis</i> sp.	0										
* <i>Gomphonema exiguum</i> v. <i>arctica</i>											
* <i>Gomphonema kamschatcicum</i>											
* <i>Gyrosigma fasciola</i>											
* <i>Gyro-Pleurosigma</i> spp.											
<i>Navicula cancellata</i>	x			Δ				A			
<i>Navicula cancellata</i> v. <i>skaldensis</i>	O							O			
<i>Navicula directa</i>											
* <i>Navicula gracilis</i>											
* <i>Navicula peregrina</i>											
<i>Navicula spicula</i>				Δ							
<i>Navicula transitans</i> v. <i>derasa</i>	O							P			
<i>Nitzschia angularis</i>	P										
<i>Nitzschia cylindrus</i>								P			
* <i>Nitzschia frigida</i>											
* <i>Pinnularia quadratarea</i>											
<i>Stauroneis</i> sp.											
<i>Synedra</i> spp.	P							P			
Unidentified tube-forming species								A			
Unidentified pennate diatoms	Δ			Δ				A			
Centric diatoms											
<i>Chaetoceros</i> sp.											
<i>Chaetoceros</i> sp. resting spore											
<i>Coscinodiscus radiatus</i>											
<i>Thalassiosira</i> sp.											
Flagellates											
<i>Dinema litorale</i>											

Table 15. Zooplankton species from samples collected off Narwhal Island, spring 1980.

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<b>Cnidaria - Hydrozoa</b>
<i>Aeginopsis laurentii</i> Brandt
<i>Euphysa flammea</i> (Linko)
<i>Halitholus cirratus</i> Hartlaub
<b>Ctenophora</b>
<i>Pleurobrachia pileus</i> (O. F. Müller)
<b>Annelida</b>
Polychaeta - unidentified larvae
<b>Echinodermata - unidentified pluteus larvae</b>
<b>Arthropoda - Crustacea</b>
Isopoda - unidentified larvae
Copepoda
<b>Calanoida</b>
<i>Pseudocalanus elongatus</i> (Boeck)
<i>Pseudocalanus major</i> G. O. Sars
<i>Pseudocalanus minutus</i> (Krøyer)
<i>Eurytemora herdmanni</i> Thompson & Scott
<i>Eurytemora richingsi</i> Heron & Damkaer
<i>Metridia longis</i> (Lubbock)
<i>Acartia longiremis</i> (Lilljeborg)
<b>Cyclopoida</b>
<i>Oithona similis</i> Claus
<i>Cyclopina gracilis</i> (Claus)
<i>Cyclopina schneideri</i> T. Scott
<b>Harpacticoida</b>
<i>Harpacticus superflexus</i> Willey
<i>Helectinosoma neglectum</i> (G. O. Sars)
<b>Mysidacea - unidentified species</b>
Amphipoda
<b>Gammaridea</b>
<i>Anonyx nugax</i> (Phipps)
<i>Apherus aglacialis</i> (Hansen)
<i>Halirages mixtus</i> Stephensen
<i>Lagunogammarus wilkitzki</i> (Birula)
<i>Onisimus litoralis</i> (Krøyer)
<b>Hyperiidia</b>
<i>Hyperia galba</i> (Montague)
<b>Decapoda - unidentified Brachyura</b>
Unidentified crustacean eggs
<b>Chaetognatha</b>
<i>Sagitta elegans</i> Verrill
<b>Chordata - Larvacea</b>
<i>Fritillaria</i> sp.
<i>Oikopleura labradoriensis</i> Lohmann
<i>Oikopleura vanhoeffeni</i> Lohmann

---

Table 16a. Relative abundance and distribution through time of zooplankton taxa other than copepods collected off Narwhal Island, spring 1980; Samples collected with a 0.75 m ring net, mesh size 308 µm. Where no symbol is present, no animals were found. P = < 1000; A = 1001 - 5000; O = 5001 - 10000; x = > 10001; - = present, but not counted.

Taxon	T	Apr							May				
		10	12	14	17	19	24	29	2	5	8	1	5
Coelenterata - Hydrozoa													
<i>Aeginopsis laurentii</i>	P				A	P	P		P			P	P
<i>Euphysa flammea</i>	Δ	P		Δ	Δ	P	P	Δ	Δ	Δ			A
<i>Halitholus cirratus</i>	P	P		P	P	P	P			P	P	P	P
Ctenophora													
<i>Pleurobrachia pileus</i>						P							
Polychaeta - unidentified larvae	P	P			P	P	P	P		P	P	P	P
Arthropoda - Crustacea													
Isopoda													
Unidentified epicaridean parasite	P								P				
Unidentified larvae													
Mysidacea - unidentified species													
Amphipoda													
Gammaridea													
<i>Lagunogammarus wilkitzkii</i>				P									
<i>Anonyx nuxax</i>	P												
<i>Onisimus litoralis</i>	A	A	A	P		P	P		P	P	P	P	P
<i>Apherusa glacialis</i>				P		P							
<i>Halirages mixtus</i>	P		P			P	P	O	P		P	P	P
Hyperiidea													
<i>Hyperia galba</i>													
Decapoda - unidentified species													
Unidentified crustacean eggs				-	-	-	-	-					
Echinodermata - plutei				A	P		x	x	x	x	x	x	x
Chaetognatha													
<i>Sagitta elegans</i>						P							
Chordata - Larvacea													
<i>Fritillaria borealis</i>			P	P	A	P							
<i>Fritillaria</i> sp.									P		P	A	
<i>Oikopleura labradoriensis</i>					P				P	P	P	P	
<i>Oikopleura vanhø feni</i>													

Table 16s. (cent. )

Taxon	May							Jun					
	17	20	22	24	26	29	31	2	5	7	9	1	1
<b>Coelenterata</b> - Hydrozoa													
<i>Aeginopsis laurentii</i>		P	P	P		P	A	P	P	P			
<i>Euphysa flammea</i>	A	A	A	P	P	P	P	P	P	P	P		
<i>Halitholus cirratus</i>			P		P		P			P	P		
<b>Ctenophora</b>													
<i>Pleurobrachia pileus</i>			P					P					
<b>Polychaeta</b> - unidentified larvae	P	P	P	P	P	P	P	P	P	A			A
<b>Arthropoda</b> - Crustacea													
Isopoda													
Unidentified epicaridean parasite				P									
Unidentified larvae					P								
Mysidacea - unidentified species							P						
Amphipoda													
Gammaridea													
<i>Lagunogammarus wilkitzkii</i>													
<i>Anonyx nuxax</i>													
<i>Onisimus litoralis</i>	P	P	P	P	P	P		Δ	Δ		A	P	
<i>Apherusa glacialis</i>													A
<i>Halirages mixtus</i>	P	P	P	P				P	P	P	Δ	O	
Hyperiidea													
<i>Hyperia galba</i>						P							
Decapoda - unidentified species									P				
Unidentified crustacean eggs													
<b>Echinodermata</b> - plutei	X	X	O	P	P	Δ	X	X	P	X			
<b>Chaetognatha</b>													
<i>Sagitta elegans</i>													
<b>Chordata</b> - Larvacea													
<i>Fritillaria borealis</i>					A	X	O	A	P	A			
<i>Fritillaria</i> sp.	P	Δ	Δ	X									
<i>Oikopleura labradoriensis</i>	P		P	P		A	O	P		P			
<i>Oikopleura vanhoeffeni</i>								P					

Table 16b. Relative abundance and distribution through time of copepods collected at Narwhal Island, spring 1980. Samples collected with a 0.75 m ring net, mesh size 308 µm. Where no symbol is present, no animals were found. P = < 1000; A = 1001 - 5000; O = 5001 - 10000; x = 10001 - 20000; ● = 20001 - 50000; + = > 50000.

Taxon		Apr								May			
		T	10	12	14	17	19	24	29	2	5	8	15
<b>Calanoida</b>													
<i>Pseudocalanus elongatus</i>	VI m	P		P	P					P	P		O
	f	P	P	P	P		Δ	Δ	P	P	P		Δ
	V m	●	Δ	Δ	x	x	+	+	Δ	●	●	●	●
	f	O	P	P	A	A	A	x	P	O	x	O	x
	IV m	+	Δ	Δ	x	●	O	O	Δ	●	●	●	●
	f	●	Δ		Δ	x	x	x	Δ	●	x	x	●
	III m												
	f											P	A
	II												A
	I												P
<i>Pseudocalanus major</i>	VI m									P	P	A	
	f							A					P
<i>Pseudocalanus minutus</i>	VI m												
	f												
	V m												
<i>Eurytemora herdmani</i>	VI m												P
	f												
	V m								P		P		
	f									P	P	P	
<i>Eurytemora richingsi</i>	IV m												
	f												
<i>Metridia longa</i>	V m		P										
	f												
III m													
f													
II				P	P			P		P			

Table 16b. (cent. )

Taxon		T	Apr							May				
			10	12	14	17	19	24	29	2	5	8	15	
<i>Acartia longiremis</i>	VI m	P						Δ	P		P	P	P	A
	f	P	P		P	P		A	P		Δ	P	P	O
	V m													
	f		P		P	P		P	P				P	P
<b>Cyclopoida</b>														
<i>Oithona similis</i>	VI m													
	f													
<i>Cyclopina gracilis</i>	VI m													
	f													
<i>Cyclopina schneideri</i>	VI m													
	f													
<b>Harpacticoida</b>														
<i>Harpacticus superflexus</i>	VI m												P	P
	f													
	juveniles				P									P
<i>Helectinosoma neglectum</i>	VI m													
	f													
	juveniles								P					

Table 16b. (cent. )

Taxon		17	20	22	May				Jun					
					24	26	29	31	2	5	7	9	1	1
Calanoida														
<i>Pseudocalanus elongatus</i>	VI m	O	A	+	●	+	x	x	O	Δ	P	Δ	Δ	
	f	P	Δ	●	x	●	x	x	x	Δ	Δ	Δ	Δ	●
	V m	●	●	+	+	+	●	x	x	A	P	A	A	
	f	●	x	+	+	+	+	●	●	O	Δ	O	x	
	IV m	x	O	+	●	+	O	Δ	Δ	P	P	Δ	Δ	
	f	●	x	+	+	+	●	x	●	Δ	P	Δ	O	
	III m		P		A				P			P	x	
	f													
	II			x	x	●	Δ	A	A	P	P			0
	I			A			P				P			
<i>Pseudocalanus major</i>	VI m													
	f	P	P		x									
<i>Pseudocalanus minutus</i>	VI m													
	f	P	P					P						
	V m							P						
	f													
<i>Eurytemora herdmani</i>	VI m		P											
	f							P		P		P	P	
	V m													
	f													
	IV m													
	f													P
<i>Eurytemora richingsi</i>	V m													
	f													
<i>Metridia longis</i>	V m													
	f							P						
	III m									P	P			
	f													
	II													

Table 16b. (cent. )

Taxon		17	20	22	May 24	26	29	31	2	5	Jun 7	9	11
<i>Acartia longiremis</i>	VI m	Δ			A			P			P		
	f	A	A			A	A	P		P	P	P	
	V m	P											
	f												
<b>Cyclopoida</b>													
<i>Oithona similis</i>	VI m		P				P	P		P	P	P	
	f												
<i>Cyclopina gracilis</i>	VI m										P		
	f												
<i>Cyclopina schneideri</i>	VI m										P	P	
	f												
<b>Harpacticoida</b>													
<i>Harpacticus superflexus</i>	VI m		P	A		A		A	P	Δ	O	●	●
	f							x		P	A	x	+
<i>Helectinosoma neglectum</i>	juveniles		P		A		P	P		Δ	O	●	●
	VI m								P	P	Δ	P	
	f								P	P	P	P	P
	juveniles									P	P		

planktonic species *Aeginopsis laurentii*. Polychaete larvae were always present, as well as echinoderm plutei, indicating reproduction of these benthic groups. Unidentified crustacean eggs were present during late April.

The amphipods *Onisimus litoralis* and *Halirages mixtus* were common throughout the spring. Present on occasion were *Lagunogammarus wilkitzkii*, *Anonyx nugax*, *Apherusa glacialis*, and *Hyperia galba*. The larvaceans *Fritillaria borealis* and *Oikopleura labradoriensis* were usually present.

## 5. Nutrients and salinity

The concentrations of inorganic plant nutrients are given in Table 7. Data from ice cores should be considered as minimum values because they were obtained from melted cores, that were diluted by an unknown amount from the melting ice.

Nitrate in the water column remained near  $10 \mu\text{g-at } \ell^{-1}$  throughout the study period, and was *ea.*  $1 \mu\text{g-at } \ell^{-1}$  higher at 7 m than at the surface (Fig. 10). This is comparable to levels found during the winter near Barrow (Matheke 1973) and near Prudhoe Bay (Homer *et al.* 1974). Water samples collected in Stefansson Sound during May 1979 had significantly less nitrate, *ea.*  $1.5 \mu\text{g-at } \ell^{-1}$  at the surface and *ea.*  $4.5 \mu\text{g-at } \ell^{-1}$  at 4 m.

In the ice, the nitrate concentration was approximately equal to surface water levels from April to mid-May. During the peak of the ice algal bloom, mid-May to early June, the concentration increased dramatically to  $15\text{-}20 \mu\text{g-at } \ell^{-1}$  for approximately two weeks, and then declined to previous levels. The source of this nitrate is not known, but may have resulted from brine drainage or microbial activity (Schell 1974). A similar pulse of nitrate was observed in the interstitial water of the sediments and in bottom water near Barrow (Matheke 1973).

Nitrite concentrations remained low and at nearly constant levels. Nitrite was highest in the ice, averaging  $0.19 \mu\text{g-at } \ell^{-1}$ , and lowest at 0 m,  $0.08 \mu\text{g-at } \ell^{-1}$ , while at 7 m, the concentration was intermediate,  $0.13 \mu\text{g-at } \ell^{-1}$ .

Ammonia was highest in the ice, *ea.*  $1.2 \mu\text{g-at } \ell^{-1}$ , and decreased with depth, averaging  $0.14 \mu\text{g-at } \ell^{-1}$  at 0 m, and  $0.03 \mu\text{g-at } \ell^{-1}$  at 7 m. A slight increase in ammonia concentration was seen in the ice during the peak of the ice algal bloom, and high levels,  $4.33 \mu\text{g-at } \ell^{-1}$ , were found near the end of the bloom on 9 June.

Phosphate concentrations were generally *ea.*  $1.5 \mu\text{g-at } \ell^{-1}$ , which is similar to winter levels reported from Point Barrow (Matheke 1973) and from Prudhoe Bay (Homer *et al.* 1974). No difference was seen between concentrations in the ice and water column. Several anomalous peaks in phosphate concentration, up to  $25 \mu\text{g-at } \ell^{-1}$ , were seen, but we have no explanation for these peaks at present.

Silicate concentrations were nearly constant, averaging  $22 \mu\text{g-at } \ell^{-1}$

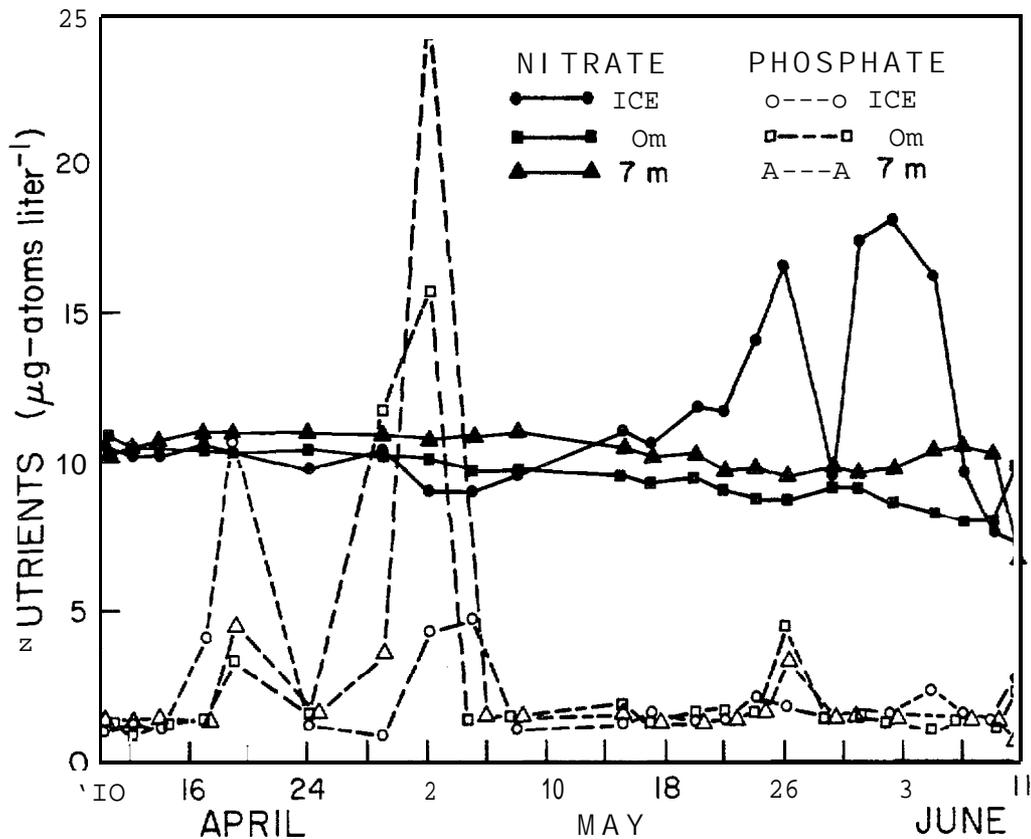


Fig. 10. Nitrate and phosphate concentrations ( $\mu\text{g-at } \ell^{-1}$ ) from ice cores and at 0 and 7 m in the water column, spring 1980.

in the ice and at the water surface, being only slightly higher,  $24 \mu\text{g-at } \ell^{-1}$ , at 7 m.

Salinity was ea.  $34.5\text{‰}$  at the surface, and increased by ea.  $1\text{‰}$  at 7 m (Table 7, Fig. 11). During the last two weeks of May, salinity dropped ea.  $1\text{‰}$ , which may have been because of overflow from the Sagavanirktok River. Salinity increased slightly before dropping abruptly in June when the ice began to melt, causing the water column to become highly stratified, with over  $10\text{‰}$  difference between the surface and 7 m. Salinity in the ice was variable and somewhat lower than at the surface, probably caused by melting ice in the core samples.

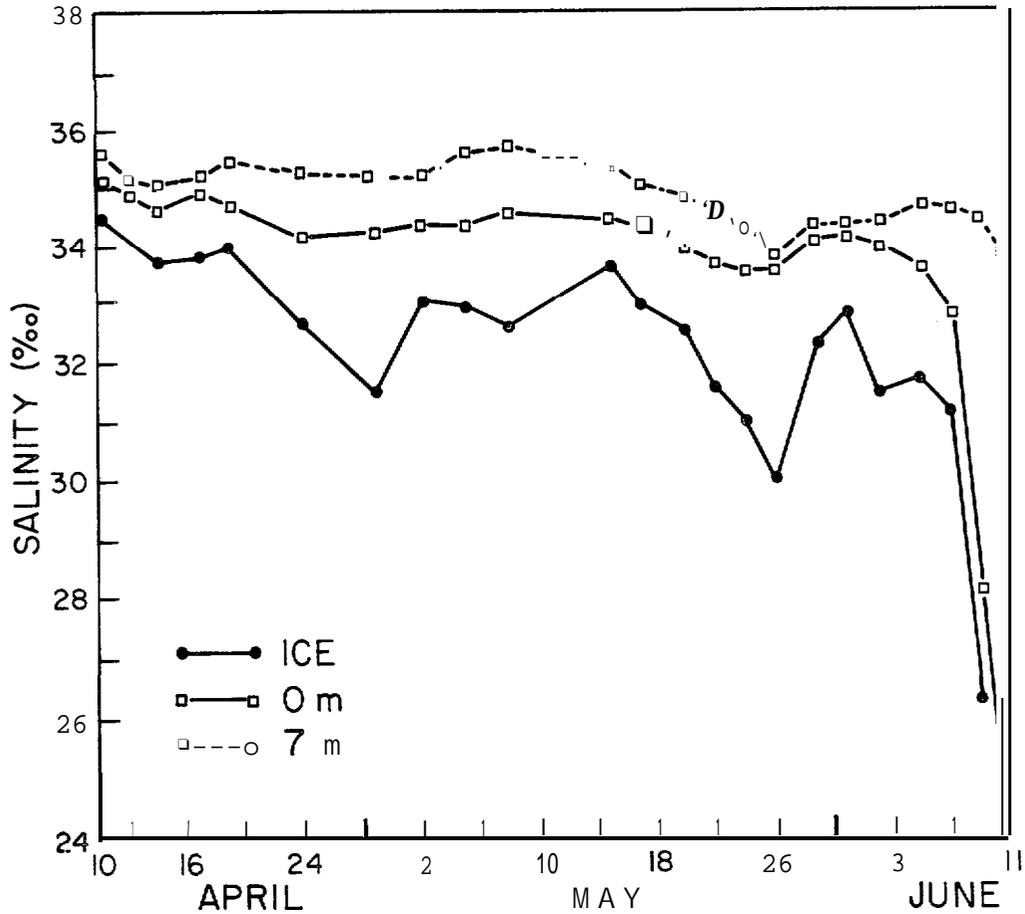


Fig. 11. Salinity (‰) from ice cores and at 0 and 7 m in the water column, spring 1980.

## 6. Light

Measurements of incident solar radiation ( $\mu\text{E m}^{-2} \text{ see}^{-1}$ ) and light intensity in the bottom ice above the algal layer, and at 0 and 7 m are presented in Table 17. Light data before 2 May are not available because of a malfunction of the light meter.

Incident light, measured near local apparent noon, was variable and more a function of local weather than of the increasing elevation of the sun with time (Fig. 12). The average surface light intensity was lower during mid-May to early June.

Light penetrating the ice and reaching the top of the algal layer generally fluctuating between 0.5 and 1.5% of surface light during the period of snow cover (Fig. 13). After the snow cover melted (29 May), light levels increased sharply, fluctuating between 1.5 and 4% of surface values. In the water directly beneath the algal layer, 0 m, light levels generally fluctuated between 0.4 and 0.8% of surface light. Levels did not generally increase in response to decreasing snow cover, because of the shading effect

of the growing ice algal layer. Light reaching the benthos was very low, remaining at ea. 0.2% of surface levels throughout the study. The highest light intensity recorded at 7 m was only 0.6% of the surface level.

In order to describe in more detail the effect of snow depth on sub-surface light, a series of six transects was run: four through a snow drift that formed in the lee of the tent, and two directly over the area where primary productivity samples were incubated. The percentage of light transmitted through the ice and snow was measured before and after removal of the ice algal layer, in snow depths ranging from 0-40 cm (Appendix II-4). Given a constant or zero snow depth, light reaching the underside of the ice varied by as much as a factor of 2. The extinction coefficient and percentage of surface light transmitted through the ice and snow are listed in Table 18. Only 3-4 cm of snow was required to reduce light reaching the underside of the ice to < 1%; 6 cm reduced light to 0.5%; and 20 cm reduced light to < 0.1% of surface levels. An inverse relationship was found between snow depth and light attenuation by the algal layer, indicating decreasing algal growth with increasing snow depth.

Table 17. Light intensity, percentage of surface light, and snow depth off Narwhal Island, spring 1980. Data are the average of measurements taken at the beginning and end of primary productivity experiments.

Date	$\mu\text{E m}^{-2} \text{ sec}^{-1}$				Percent Surface			Snow Depth
	Surface	Ice	0m	7m	Ice	0 m	7m	(cm)
May 2	1125	7.4	5.8	2.4	0.7	0.5	0.2	6.0
5	1075	15.3	9.6	2.2	1.4	1.0	0.2	3.5
6	1385	13.6	12.7	2.5	0.9	0.8	0.2	3.0
8	1375	7.2	10.9	3.3	0.5	0.8	0.2	2.0
15	1275	8.4	4.8	1.7	0.6	0.4	0.1	3.0
17	1250	9.3	4.9	2.1	0.7	0.5	0.2	2.5
19	1350	15.8	9.3	3.1	1.2	0.7	0.2	2.5
20	1035	15.0	7.1	2.4	1.5	0.7	0.2	2.0
22		14.0	9.4		1.1	0.7		3.0
26	1265	10.5	4.4	2.6	0.9	0.4	0.2	1.0
29	1110	19.3	8.8	6.5	1.7	0.8	0.6	0.0
31	835	16.6	7.9	2.3	2.0	0.9	0.3	0.0
Jun 2	1165	21.4	5.8	2.3	1.9	0.5	0.2	0.0
3	1130	16.1	3.9	2.1	1.4	0.3	0.2	0.3
5	975	13.3	5.9	1.4	1.3	0.6	0.1	0.0
7	885	32.4	18.9	2.9	4.0	2.7	0.3	0.0
9	1235	22.3	4.9	3.0	1.8	0.4	0.2	0.0
11	1175	33.7	18.1	2.7	2.8	1.5	0.2	0.0

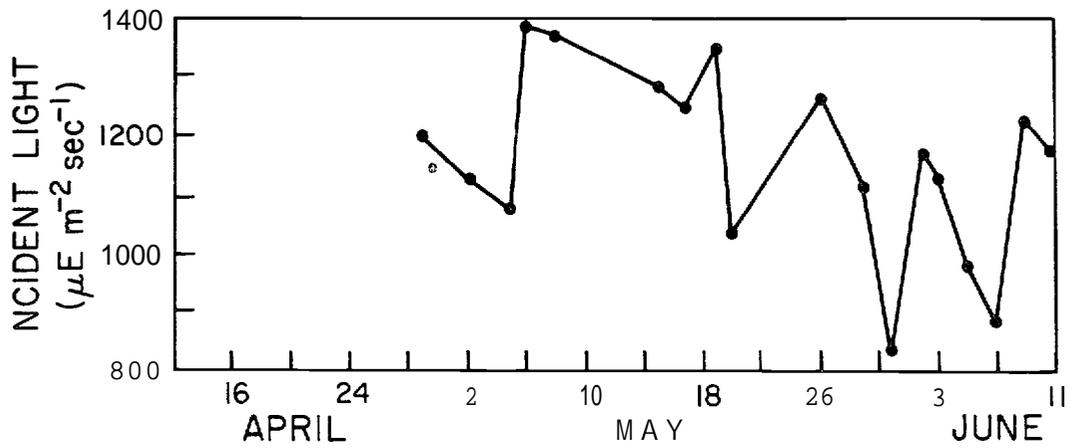


Fig. 12. Incident light intensity ( $\mu\text{E m}^{-2} \text{ sec}^{-1}$ ) measured near local apparent noon, spring 1980.

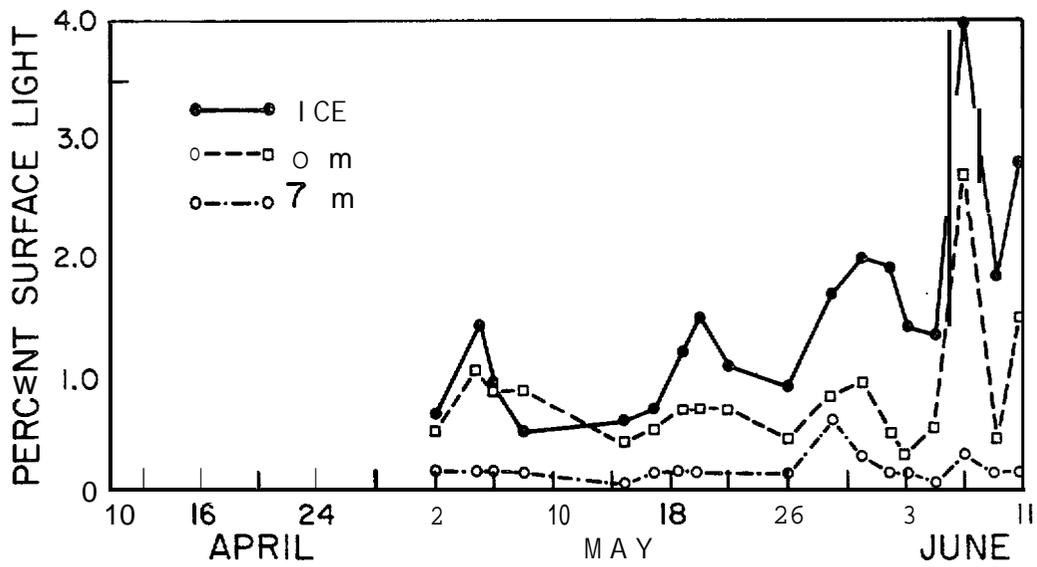


Fig. 13. Percent surface light reaching the ice algal layer and at 0 and 7 m in the water column, spring 1980.

## 7. Surface weather observations

Surface weather and snow observations are listed in Appendix II-1.

Air temperatures in early April were generally  $-10$  to  $-20^{\circ}\text{C}$ , and gradually increased, so that by 24 May, the air temperature was about equal to the surface water temperature.  $-1.8^{\circ}\text{C}$ . The highest air temperature was  $9.5^{\circ}\text{C}$ , recorded during a period of clear, calm weather on 9-11 June.

Snow depth was generally 2-5 cm with drifts to 50 cm. Drifts formed at the north and south ends of the tent, but samples were collected in areas free of drifts. The snow began to melt on 26 May and had completely disappeared and melt ponds had begun to form by 29 May. By 9 June, the top of the ice was melting rapidly and the dive hole had become a major drainage point for meltwater.

Sea ice was accreting during most of the study period. The ice thickness was 169 cm on 24 April, and had increased to a maximum of 178 cm on 2 June.

The sky was generally overcast during the study period, and winds were typically 10-20 kt, from  $030^{\circ}$  magnetic. Blowing snow and fog were common and helicopters were often grounded because of poor visibility. This restricted sampling to periods of clearer weather.

Table 18. Snow depth, mean extinction coefficients ( $k_{m^{-1}}$ ), and percent surface light for six transects taken during spring 1980. Light measurements were taken above the ice algal layer.

Snow Depth (cm)	Surface Light (%)	k ( $m^{-1}$ )	Replicates (N)
0	2.10	0.99	21
.25 - .99	1.34	1.14	4
1 - 1.9	1.51	1.06	5
2 - 2.9	1.33	1.09	33
3 - 3.9	0.85	1.18	11
4 - 4.9	0.43	1.35	4
5 - 5.9	0.53	1.30	5
6 - 6.9	0.28	1.55	3
7 - 8	0.43	1.39	3
10 - 11	0.23	1.42	1
12 - 15	0.31	1.38	3
16 - 20	0.13	1.53	7
21 - 25	0.07	1.61	3
26 - 30	0.05	1.73	4
31 - 40	0.02	1.83	6
41 - 50	0.01		6

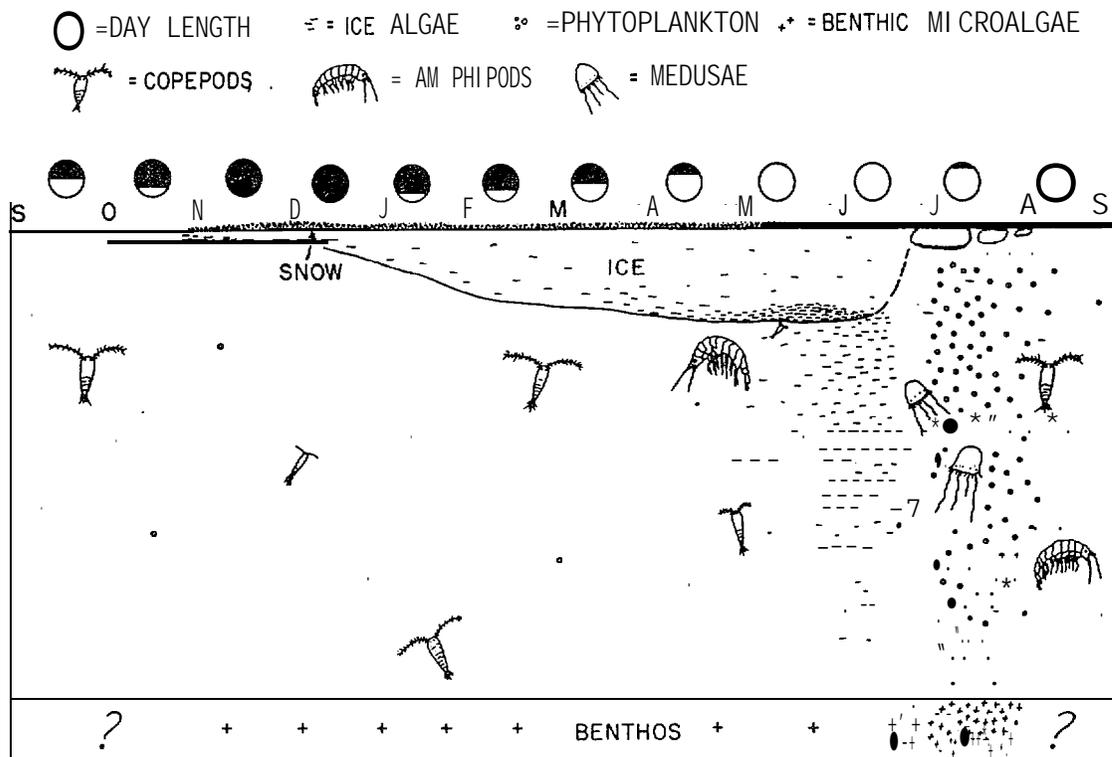


Fig. 14. Schematic representation of the annual cycles of ice algae, phytoplankton, benthic microalgae, and zooplankton in the nearshore area of the Beaufort Sea and Stefansson Sound.

## VII. Discussion

Figure 14 is a schematic presentation of the annual cycle of ice algae, phytoplankton, benthic microalgae, and zooplankton for the near-shore area of the Beaufort Sea and Stefansson Sound.

### A. Ice algae

Microalgae are present in the sea ice as soon as it forms in the fall with microflagellates being the most abundant organisms (Horner 1976). The origin of the cells is uncertain. Few species of ice algae are members of the fall phytoplankton community which is dominated by centric diatoms (Homer 1969), rather than the flagellates and pennate diatoms found in the ice. It is possible, however, that ice algae species are present in the water column in such low numbers that they are not collected by conventional sampling techniques. As the ice forms, algal cells become trapped in brine pockets and natural selection favors species adapted to this habitat.

Newly formed sea ice may also be seeded from ice algae still associated with drifting pack ice that persists throughout the summer. Meguro *et al.* (1966, 1967) reported a rich ice algal layer 5-30 cm thick in the soft bottom of pack ice off Barrow, Alaska, during July and August that contained species typical of the spring ice algal community (Homer and Alexander 1972). However, it is not known if cells persist in the drifting pack ice as late as freezeup. This mechanism of seeding may contribute to the observed patchy distribution of the ice algae.

Another possible source of seed stock for the ice algae may be from sediments that become resuspended during the fall storms in nearshore areas. However, although some species are common to both habitats, many species found in the ice, including several of the most abundant species, are not found in the sediments (Matheke and Homer 1974). This mechanism would only be operative in nearshore areas where resuspended sediments could reach the surface, or in areas where sediments may be advected by currents.

Growth of the diatoms in the ice in the fall probably continues until mid-November when light becomes limiting, although few reports are available to confirm this. Hsiao (1980) reported a layer of ice algae concentrated near the bottom of sea ice 50 cm thick in late November in the Eskimo Lakes region of the Canadian Arctic. In the western Beaufort Sea, a core taken on 9 November 1980 by RU 537 from our study area off Narwhal Island, contained a rich algal layer in the bottom ice, with diatom concentrations of  $1.8 \times 10^8$  cells  $m^{-2}$ , which was comparable to levels found during the 1980 spring bloom. The cells were healthy, and the species composition was similar to that found in the ice the preceding spring. An autumnal bloom has been reported to be a normal event in Antarctic sea ice (Hoshiai 1977).

Heterotrophy has been suggested as a mechanism by which algae survive the prolonged darkness of Arctic winter (Rodhe 1955; Wilce 1967; Allen 1971). Experiments using a variety of labeled organic substrates and four species of algae isolated from Antarctic sea ice failed to show heterotrophic growth in the dark (Bunt and Lee 1972). They concluded that dark survival for many Antarctic species did not depend on external substrates. In the Arctic, Homer and Alexander (1972) found that heterotrophic metabolism by natural populations of ice algae was negligible, and assimilation of labeled organic substrates was almost exclusively by bacteria.

Recent work on dark survival has shown that many algal species maintain viability for long periods of total darkness. Antia (1976) tested the viability of 37 species of marine planktonic algae from 10 taxonomic classes. Most species maintained viability for 5-6 mo in media free of organic substrates at temperatures ranging from 2-20°C. Benthic species (pennate diatoms) were more resistant, with some species remaining viable for over one year and a few species for up to three years of darkness. At the low temperature, ca. -1.8°C, to which ice algae are adapted, metabolic requirements should be low and species should easily tolerate the 4-5 mo of darkness during the Arctic winter.

During the winter, cells are found scattered throughout the ice (Homer 1976; Hsiao 1980), but by mid-March, the algae become concentrated at the bottom of the ice. How the cells become concentrated is not known, but it may be the result of brine drainage and active migration of the algal cells through brine channels. Brine cells are small pockets of hypersaline water formed as salts are excluded during ice formation (Pounder 1965). These pockets migrate downward through the ice by diffusion and gravity. Brine drainage becomes more rapid as the ice warms in spring and microalgae living in the pockets are transported to the bottom of the ice. The diatoms, themselves, may assist this migration because many pennate diatoms are able to move with a slow, gliding movement.

Light is probably the major factor controlling the distribution, devel-

opment, and production of the ice algal community with growth of the ice algae beginning in spring in response to increasing light. At Barrow, Alexander *et al.* (1974) measured rates of primary production at varying light intensities. Productivity remained  $< 0.1 \text{ mg C m}^{-2} \text{ hr}^{-1}$  until a threshold level was reached. Above this level, 2.3 and  $9.3 \mu\text{E m}^{-2} \text{ sec}^{-1}$  in successive years, production was rapid. In 'Davis Strait, Maclaren Marex (1979) reported maximum productivity at  $1.8 \mu\text{E m}^{-2} \text{ sec}^{-1}$ , but their reported productivity was nearly always  $< 0.1 \text{ mg C m}^{-2} \text{ hr}^{-1}$ . Off Narwhal Island in spring 1980, productivity began to increase when the light level was  $7.4 \mu\text{E m}^{-2} \text{ sec}^{-1}$ , which is similar to the threshold levels reported by Alexander *et al.* (1974).

In nearshore areas, light may be severely limited by sediments trapped in the ice. In early April 1980, a series of ice cores collected with a SIPRE corer in Stefansson Sound revealed a layer or layers of sediment throughout the lagoon system, and no algal layer was detected. Divers sampled the boulder patch area of Stefansson Sound on 11 May and found only a trace amount of chlorophyll *a* at a time when productivity was high outside the lagoon. This is in contrast to 1979 when in the same area, the algal layer was well-developed, although patchy. Schell (1980a) reported that light attenuation by turbid ice was the controlling factor of ice algal development in Stefansson Sound. It appears that in shallow areas, the distribution of sediments in the ice may largely determine the extent of the ice algal layer, and thus, the spring productivity of the lagoon system.

Where ice does not contain sediment, light attenuation because of snow is the prime factor controlling the distribution and productivity of ice algae. The light attenuating property of snow is very high compared with that of clear sea ice (Thomas 1963). Off Narwhal Island we found that an average of 2% of surface light reached the algal layer when no snow was present, but that 3-4 cm of snow reduced light to  $< 1\%$ , ea.  $15 \mu\text{E m}^{-2} \text{ sec}^{-1}$ ; 6 cm to  $< 0.5\%$ ; and 20 cm to  $< 0.1\%$ . Alexander *et al.* (1974) observed that patchy distribution of the ice algae was correlated with light attenuation due to snow, and found an inverse relation between chlorophyll *a* and snow depth. Transects through snow drifts off Narwhal Island showed the same relationship, with a decrease in the algal layer with increasing snow depth.

At Barrow, maximum productivity occurred at light levels of ca.  $16-65 \mu\text{E m}^{-2} \text{ sec}^{-1}$  ( $0.3-1.2 \text{ ly hr}^{-1}$ ) (Alexander *et al.* 1974) and off Narwhal Island at  $10-25 \mu\text{E m}^{-2} \text{ sec}^{-1}$ . Productivity over the entire bloom period was ea.  $5 \text{ g C m}^{-2}$  at Barrow and only  $0.7 \text{ g C m}^{-2}$  off Narwhal Island. In both areas, productivity increased in response to increasing light levels and maximum productivity occurred after the snow had gone. The observed differences in productivity between the two areas was probably the result of different light levels caused by ice turbidity and snow, with light being more limiting off Narwhal Island.

During early development of the bloom off Narwhal Island, divers noted more algal growth near stalactites that form when brine drains down through vertical channels in the ice (R. Poirot, J. Dougherty pers. comm.). Lewis and Milne (1977) reported increased light levels in stalactites that apparently act as funnels for light penetrating the ice. The higher light levels, and perhaps the increased nutrient concentrations from brine

drainage, appear to encourage algal growth which may provide a concentrated food source for grazing invertebrates. Amphipods have been reported living within the crystal structure of the stalactites (Lewis and Milne 1977; Dunton pers. comm.) and have remained at the site after the stalactites were removed, apparently taking advantage of the localized food source.

At the time of the spring ice algal bloom, nutrient concentrations at the water surface were high because of vertical mixing and regeneration during winter when plant utilization is low. Nutrient levels in the ice may be even higher than at the surface because of brine drainage and local recycling. That recycling of nutrients occurs is evidenced by the pulse of nitrate during the bloom (Fig. 10). Nitrate in the ice rose to nearly twice the surface water values and probably resulted from vitrification by the microbial population. Vitrification is the oxidation of ammonia, a product of animal metabolism, to nitrite and nitrate. The ammonia concentration was high during the bloom, which suggests heavy grazing pressure. In the bottom water, 7 m, ammonia remained near the limit of detection throughout the study period, suggesting the relative lack of animal activity at that depth.

River overflow may also have a significant effect on surface nutrient concentrations in the lagoon system. In May 1979, river overflow was evident by a lens of low salinity, nutrient-poor water just below the ice. Nitrate and phosphate concentrations in the surface water were about one-fourth the levels at 4 m. The silicate concentration was higher at the surface, reflecting the high levels of silicate in rivers draining into the Beaufort Sea (Hufford 1974b). Nutrients were probably not limiting, however, because productivity was equal to, or exceeded, productivity off Narwhal Island in 1980.

During the spring bloom off Narwhal Island, surface salinity was fairly constant, 34-35‰, until early June when melting ice and river runoff caused salinity to drop below 25‰. River runoff was detected ca. two weeks before the sea ice began to melt. The algal layer began to soften and dissociate from the harder bottom ice and was easily disturbed by bubbles from the diver's breathing apparatus. Several dominant ice algal species, such as *Nitzschia cylindrus* and *Navicula spicula* appeared to be unhealthy, and productivity dropped for about one week. These events also coincided with the disappearance of the snow and it is likely that increasing radiation contributed to the disintegration of the ice algal layer because of selective absorption by diatoms (Meguro *et al.* 1966, 1967).

Ice diatoms are able to withstand a wide range of salinity. Grant and Homer (1976) measured the salinity tolerance of four species of ice algae collected near Barrow and found rapid growth over a broad range of salinities from ca. 10-50‰. At ca. 60‰, growth was limited, and they suggested that high brine cell salinity may limit the upward penetration of ice algae into the sea ice. Schell (1980a, 1980b) suggested that surface water salinity over 40‰ may have been partly responsible for low ice algal density in Simpson Lagoon when clear ice was present, but this seems unlikely in view of the salinity tolerances reported by Grant and Homer (1976) and because ice algae usually live in brine pockets in the ice.

Off Narwhal Island, the ice algae were associated with the bottom ice

in a loose, slush layer for a week after the ice had begun to melt, but by 11 June, no layer was visible and the water was clouded with ice algae. Microscopic examination of cells from the water showed that they were not healthy and primary production in the water column was almost undetectable.

The fate of the ice algae in Stefansson Sound and off Narwhal Island is not known. No data are available after the ice algae leave the ice and there is no information for the period of ice breakup or for the spring phytoplankton bloom. The summer plankton situation near Prudhoe Bay (Homer *et al.* 1974) and beyond the 10 fm line (Homer 1981) have been documented. Perhaps the ice algae cells are rapidly dispersed in the water column and are not collected in water sampling bottles (Homer 1976). Many cells probably do not survive as already suggested. Some cells may settle to the bottom, but the dominant species from the ice are not the same as the dominant species from the benthos (Matheke and Homer 1974).

At Barrow, the ice algal bloom and the spring bloom in the water column are separated by species present and time. The ice community consists primarily of pennate diatoms (Homer and Alexander 1972; Alexander *et al.* 1974), while the spring phytoplankton bloom consists primarily of centric diatoms (Homer 1969). Only one species, *Nitzschia cylindrus*, is common in both the ice and water column communities. The ice algal bloom occurs in April and May, sometimes extending into early June, while the phytoplankton bloom does not start until ice breakup is underway and light is available to the cells in the water column. In shallow, coastal waters the phytoplankton bloom may be delayed somewhat by the low salinity of the water column caused by the melting ice.

Elsewhere, Saito and Taniguchi (1978) reported what they called "ice plankton," or species that probably grew in sea ice, in deeper water in the Bering and Chukchi seas during summer, but whether these cells remain viable and, if brought back into the surface water, they are able to seed new ice in the fall is not known. These authors, however, did not actually sample the ice to determine the species present in the ice.

The species composition of the ice algal community off Narwhal Island and in Stefansson Sound was similar to that reported from other areas of the Arctic (Meguro *et al.* 1966, 1967; Homer and Alexander 1972; Homer *et al.* 1974; Hsiao 1980). The community was dominated by pennate diatom species, and although centric diatoms and dinoflagellates occurred, they were represented by few species and were seldom abundant. Several identifiable flagellate species were present in low numbers, while unidentified flagellates were often abundant. A single pennate diatom, *Nitzschia cylindrus*, accounted for nearly 50% of the population off Narwhal Island. *Nitzschia frigida*, *Navicula directs*, *Navicula transitans*, *Cylindrotheca closterium*, and *Amphora ocellata* were also numerically important species.

Hundreds of diatom species have been identified from Arctic sea ice, but only a few species have been reported as dominant. Of 58 species enumerated from our samples, only six species ever accounted for more than 10% of the cells counted. Homer and Alexander (1972) found that *Nitzschia frigida* was usually the most abundant species at Barrow, but was apparently not found farther offshore by Meguro *et al.* (1966, 1967). It was often important in the community off Narwhal Island, in Stefansson Sound, and in

the Canadian Arctic (Dunbar and Acreman 1980; Hsiao 1980). *Navicula marina* was also a prominent member of the community at Barrow, and was often the most abundant species (Alexander *et al.* 1974). This species was found in the community off Narwhal Island, but was never abundant.

*Nitzschia cylindrus* is frequently reported as a dominant ice algal species and has also been reported as a member of the summer phytoplankton community (Horner *et al.* 1974; Dunbar and Acreman 1980). It is difficult to identify accurately in routine counting and the taxonomy of this and closely related species has recently gone through several changes at the generic level, being transferred from *Fragilaria* Lyngbye, to *Fragilariopsis* Hustedt, to *Nitzschia* Hassall. *Nitzschia cylindrus* is easily confused with *N. grunowii*, which has also been reported as a dominant ice algal species (Homer 1976; Dunbar and Acreman 1980).

Changes in community structure accompanied the development of the bloom off Narwhal Island. During April and early May, the community was strongly dominated by *Nitzschia cylindrus*, but in mid-May this species became less healthy and empty frustules were common in the ice and water column. As the relative numbers of *N. cylindrus* declined, other diatom and flagellate species which had been rare or had not been identified previously became common, and the diversity of the community increased. An increase in standing stock (chlorophyll a) accompanied this shift in community structure.

Environmental factors may have contributed to these species changes. Light inhibition has been suggested as a factor limiting the ice algal bloom (Apollonio 1965) and it is possible that increasing light intensity resulting from snow melt may have favored more light adapted species. Salinity declined during the peak of the bloom and, although ice algae are known to tolerate a wide range of salinities (Grant and Homer 1976), the specific requirements of *Nitzschia cylindrus* are not known and the reduced salinity may have been more favorable to the development of other species. The *nitrate* increase at the same time may have favored species that prefer higher nitrate concentrations.

The development of the spring ice algal bloom off Narwhal Island is similar to that reported by Alexander *et al.* (1974) for the Chukchi Sea near Barrow, which is the only other study to include the complete cycle of the ice algal bloom. Algal biomass (chlorophyll a) off Narwhal Island exhibited the same bimodal distribution and timing, and reached comparable peak values. An early peak occurred in late April to early May during both studies, with high values of ea. 8 mg chlorophyll a m<sup>-2</sup>. A later and maximum peak occurred at the end of May to early June with 26.5 mg Chl a m<sup>-2</sup> reported at Barrow and 23 mg Chl a m<sup>-2</sup> off Narwhal Island. Primary productivity followed a similar pattern in both studies, remaining relatively low until mid-May and climbing sharply to peak levels with a maximum during the last week of May. Total production for the bloom off Narwhal Island was about one-seventh that reported for Barrow and may have been due largely to lower light levels found off Narwhal Island.

Primary productivity was much lower at Narwhal Island than at Barrow, although both studies reported comparable levels of chlorophyll a. This suggests that it is misleading to compare or estimate productivity of

different areas based only on measurements of chlorophyll a. The difficulties of trying to determine the carbon to chlorophyll ratio (F) used to convert chlorophyll a to algal carbon are well-known (Banse 1977). The most important environmental factors that affect this ratio include nutrient concentrations, light, and temperature in that order, but species differences and interactions between factors are also important (Banse pers. comm.). Direct chemical measurements of algal carbon in natural populations are difficult because of the presence of unknown quantities of zooplankton and detrital carbon; the use of glass fiber filters also overestimates algal carbon. There are seasonal variations as well, for example when nutrients are low, the ratio is high. Strickland (1960) thought that choosing conversion factors from environmental data could not be correct to better than a factor of 0.3 to 3 and this has not changed much (Banse 1977).

The carbon to chlorophyll ratio can also be estimated microscopically by counting and measuring cells, determining mass, and converting to algal carbon. This method has serious drawbacks, as well, including the enormous amount of time needed to count and measure cells, the problem of losing unknown numbers and kinds of cells when samples are preserved, and the problem of changes in carbon:cell volume ratio that depends on the growth conditions of the cells (see Banse 1977 for discussion and references).

It is difficult to compare rates of primary productivity measured off Narwhal Island with other areas of the Arctic because few measurements have been made and methods generally have been different. Schell (1980a, b) included a table comparing annual ice algae productivity for areas of the Bering, Chukchi, and Beaufort seas based on literature values from  $^{14}\text{C}$  measurements (McRoy and Goering 1976; Alexander *et al.* 1974; Horner *et al.* 1974; Homer 1980) and values calculated from biomass (chlorophyll a) measurements. (The annual value of  $24 \text{ g C m}^{-2}$  from McRoy 1976 [should be McRoy and Goering 1976] should read  $24 \times 10^6$  metric tons and is the calculated annual budget for the whole Bering Sea shelf.) This table suggests that our measured annual productivity off Narwhal Island,  $0.7 \text{ g C m}^{-2}$ , is low when compared with other areas with the exception of Simpson Lagoon, calculated to be  $0.18 \text{ g C m}^{-2}$ .

Estimates of primary production based on direct  $^{14}\text{C}$  measurements, reported from Arctic regions, are listed in Table 19. The highest production was reported from near Barrow and was 2-7 times higher than that from off Narwhal Island. In the Bering Sea and Davis Strait, production was lower than either Stefansson Sound or Narwhal Island by a factor of 10. The literature suggests that the algal production is high along the north coast of Alaska compared with the Bering Sea and Davis Strait, but only a few experiments have been done in most areas. Production off Narwhal Island and in Stefansson Sound was low when compared with Barrow, but relatively high in relation to other areas of the Arctic where primary productivity measurements have been made.

## B. Phytoplankton

Phytoplankton was present in low numbers during the winter, with unidentified flagellates, mostly  $< 10 \mu\text{m}$ , being the most abundant organisms. By April, diatoms were more abundant, both in numbers and species, but microflagellates were still numerically dominant. Most of th

Table 19. Ice algal primary productivity measured by  $^{14}\text{C}$  uptake experiments and chlorophyll *a* values from Arctic regions.

Location	No. Stations	Primary Productivity			Chl <i>a</i> (max) mg m <sup>-2</sup>	Source
		(max) hr <sup>-1</sup> (mg C m <sup>-2</sup> )	(max) day <sup>-1</sup>	annual (g C m <sup>-2</sup> )		
Bering Sea	3		4.8	0.3 *	3.0	McRoy & Goering 1974
Davis Strait	11		2.4		0.8	MacLaren Marex 1979
Davis Strait	5		2.0*	0.15	0.5	Andersen 1977
Barrow, Alaska	25	4.56	109		30.5	Clasby <i>et al.</i> 1973
Barrow, Alaska	15	14.92	358 *	5	23.0	Alexander <i>et al.</i> 1974
Stefansson Sound	4	1.50	36	0.9 *	3.0	Homer 1980
Narwhal Island	25	2.70	63	0.7	26.5	This study

\* Values calculated from data presented

diatoms were pennate species that had probably fallen out of the ice. Only a few centric diatom species were present, with *Thalassiosira gravida* becoming more common late in the spring. This species is often abundant during the spring bloom, but none of the other typical spring bloom species occurred during our sampling program.

Chlorophyll *a* was low,  $< 0.1 \text{ mg m}^{-3}$ , during the winter, increasing to  $1.4 \text{ mg m}^{-3}$  on 11 June, the last sampling day. Phaeopigments were usually high, ea. 50%, suggesting that cells were either not photosynthetic, *i.e.*, the microflagellates, or not viable. Microscopic examination showed that many of the diatoms were in poor condition.

Primary productivity in the water column was low, usually  $< 0.1 \text{ mg C m}^{-3} \text{ hr}^{-1}$ ; maximum  $^{14}\text{C}$  uptake, only  $0.42 \text{ mg C m}^{-3} \text{ hr}^{-1}$ , occurred at the surface on 7 June.

The spring bloom in the water column probably occurs during and just after ice breakup, but more information is needed during this period between the end of the ice algal bloom and breakup to determine the origin and timing.

### C. Benthic microalgae

The annual cycle of benthic microalgae has been documented (Matheke and Homer 1974) for the nearshore area near Barrow. Growth was limited during the winter by low light levels, and productivity did not begin until the formation of melt ponds on the ice surface which, along with the disappearance of the ice algae, increased light transmission through the ice. Following breakup of the shorefast ice, benthic microalgae became the most important source of primary production in that nearshore ecosystem. Chlorophyll *a* concentrations were relatively high during the winter months when primary productivity was negligible, and the community was apparently able to survive long periods of darkness. Many of the same species were found in both the bottom ice and sediments, but some of the species in the ice, including several of the most abundant, were not found in the sediment either during or after the bloom in the ice. This suggests that ice algae probably do not contribute significantly to benthic productivity.

Our data agree with Matheke and Homer (1974). Benthic microalgae did not contribute significantly to primary productivity off Narwhal Island during spring. Productivity was limited by low light levels due to snow cover and by shading from the ice algal layer. Light levels remained low, even after melt ponds had formed and the ice algal layer "had dissolved, because of shading from algae suspended in the water column. Although productivity was extremely low, chlorophyll *a* concentrations in the sediments were relatively high throughout the spring and increased during maximum development of the ice algal bloom from algal material falling from the ice. The benthic microalgal community contained a distinct flora, dominated by species not found in the ice algal community. Few ice algal species occurred in the sediments, and most were dead or in poor condition. The most abundant species in the ice and water column, *Nitzschia cylindrus*, was represented in the sediments by a single pair of cells that had probably

fallen from the ice. Some species, such as *Navicula directa*, *N. transitans*, and *Cylindrotheca closterium*, were members of both communities, and have also been reported from the sediments and ice at Barrow (Matheke and Homer 1974) .

#### D. Zooplankton

Zooplankton species reported here are common inhabitants of the nearshore Arctic environment. Most have been reported previously in reports from RU 359 and other OCSEAP projects.

During the winter, copepods are by far the most abundant animals in the plankton. Most of the copepods in our winter samples were adults, although some stage II and III individuals of *Pseudocalanus elongatus* and *P. major* were present in November 1978.

In March 1979, young stages of *Calanus glacialis*, *Microcalanus pygmaeus*, *Pseudocalanus elongatus*, *P. major*, *Metridia lucens*, and *Oithona similis* were present, and early stages were often present, along with adults, as late as May. No really clear progression of stages occurred for any of the copepod species during the almost two years we sampled. Cairns (1967) suggested that *Pseudocalanus elongatus* may take two years to reach maturity, while Grainger (1965) thought *Microcalanus pygmaeus* and *Calanus glacialis* also took two years. This may also be the case with other copepods in our samples where there is no clear progression of stages.

Cyclopoid and harpacticoid copepods were most common in May with both juveniles and adults being present at the same time. *Oithona similis* juveniles and adults occurred in March 1979, as did adults of *Oncaea borealis*.

The most abundant copepod in our samples was *Pseudocalanus elongatus*. It is considered to be widespread in the temperate zone and at high latitudes, being abundant from the North Pacific to the North Atlantic. It is found in cold, surface waters and is more common nearshore where it can be an important food source for fish (Brodskii 1950). Two other *Pseudocalanus* species were identified: *P. major* is a neritic, strictly Arctic species found in less saline water (Brodskii 1950); while *P. minutus*, also known from neritic areas where the salinity is lower, is found from the North Pacific across the Arctic to the North Atlantic (Tidmarsh 1973).

*Metridia longa* is one of the three dominant copepods in the Arctic and Subarctic (Grainger 1962). It is reported to breed over an extended period in summer (Grainger 1959), but may start as early as March in some marginal areas. We found a few stage II's and III's and stage V females as early as April.

*Acartia longiremis* is a circumpolar Arctic species that is mostly neritic, but also occurs in surface water offshore. It is often found near melting ice (Johnson 1956). In our samples adults were found in Nov, Mar, Apr, May, and Jun, but were most abundant in Nov.

Two *Eurytemora* species were present in our samples. *Eurytemora*

*herdmani* is a littoral species found in less saline water in the Bering Sea and along the Alaskan north coast (Brodskii 1950). Johnson (1956) thought it might be an expatriate from the Bering Sea, and Redburn (1974) found it at Barrow only when the surface water was  $> 7^{\circ}\text{C}$ . *Eurytemora richingsi* was described from  $> 500$  m in the central Arctic (Heron and Damkaer 1976), but it has also been reported from shallow water in the Beaufort Sea (English and Homer 1977).

The most common cyclopoid copepod in our samples was *Oithona similis*. Adults were present during all sampling times with stages III and IV present in March. *Oncaea borealis* adult males and females were present in March. Small numbers of other cyclopoids were present in May 1979 and June 1980. The May 1979 tow was a vertical one with the net lowered to the bottom in the Stefansson Sound boulder patch where attached macroalgae were present. The species present are often reported to be found attached to plants and that may account for their occurrence in this sample. The same is also true of the Harpacticoida that were common in the same sample. However, the same harpacticoid species were also present in horizontal net tows collected off Narwhal Island in May and June 1980 where there were no attached macroalgae.

The food habits of many copepods are incompletely known. Food preference is often suggested by the type of mouth parts present (Anraku and Omori 1963), however, recent studies seem to indicate that more than one feeding mode may be used (Heron pers. comm.). *Pseudocalanus* species are apparently filter-feeders, eating diatoms, small protozoans, and scraps of detritus. Deep water species in the same family, such as *Microcalanus pygmaeus*, are mixed feeders, being able to filter out food particles and also to selectively capture prey. They use plant, animal, and detrital foods (Arashkevich 1969; Harding 1974).

Size of food particles is also important. Hargrave and Geen (1970) found that adult *Pseudocalanus minutus* and *Oithona similis* preferred microflagellates in the size range 5-15  $\mu\text{m}$  and microflagellates in this size range were present through the winter-spring period. Copepodids of *P. minutus* were opportunistic feeders and had a higher grazing and ingestion rate per unit body weight than older stages and fed continuously. Copepodids obtained more food on particles  $< .10 \mu\text{m}$  than did adults suggesting at least partially separate food niches (Poulet 1977).

Not all copepods utilize whole cells. Some cyclopoids are able to suck out cell contents and thereby make use of much larger cells than if whole cells had to be eaten (Kryuchkova 1974). The extent to which planktonic organisms use dissolved organic matter as food is not known. Perhaps its greatest importance is as a source of vitamins or growth substances (Kryuchkova 1974).

Amphipods and mysids are also important components of the nearshore ecosystem. Of these, *Lagunogammarus wilkitzkii* and *Apherusa glacialis* have been reported from the underside of the ice (Tencati 1970; Dunbar 1954), and *A. glacialis* has also been reported to be pelagic (Lewis 1969). Both are widespread, circumpolar species and generally occur in the upper 200 m. *Lagunogammarus wilkitzkii* produces one brood per year with eggs occurring

in December, and some young still in brood pouches as late as June. The life cycle of this animal may be as long as six years, suggesting low production (Tencati 1970). *Apherusa glacialis* also breeds in the area, probably in January-February (Tencati 1970). Barnard (1959) suggested that Arctic cod may selectively feed on this species.

*Onisimus litoralis* is an abundant, shallow water species usually occurring in brackish water. It is probably near its southern limit of distribution in the Beaufort Sea (Dunbar 1954). *Anonyx nugax* is a circum-polar, Arctic-Subarctic species confined to shallow water on the shelf and extending into the North Sea and the Skagerrak. It is a food species for ducks, cod, and bearded seals (Dunbar 1954).

Schneider and Koch (1979) discussed the feeding habits of some near-shore amphipods and mysids. They reported that most of the species studied ingested diatoms and peat, along with crustaceans and polychaetes. They found some suggestion of patterns of food selection, but all of the species studied appeared to be opportunistic feeders with deposit feeding being relatively important. These authors found a high proportion of benthic diatoms being utilized indicating that the benthic diatom community is an important food source for benthic and epibenthic animals, but also reported planktonic diatoms were eaten when they were available.

Hydrozoans became abundant in spring. They are probably not utilized as a primary source of food by other animals, but they do feed on copepods and other small invertebrates.

#### VIII. Conclusions

A. Ice algae are responsible for nearly all primary production during the winter-spring period, with only minimal contributions from the phytoplankton and benthic microalgae.

B. In addition to providing a rich food source for animals living in direct association with the bottom ice, ice algae provide a major source of living and detrital material for herbivores and detritivores living in the water column and benthos.

C. The ice algal community was composed primarily of pennate diatom species typical of the underice community in other Arctic regions.

D. The phytoplankton in early spring consisted almost entirely of ice algal species, most of which had fallen from the ice, and were not typical of species found during the spring and summer phytoplankton blooms.

E. The benthic microalgal community was composed mainly of species that were not found in the ice or water column. Although some species are common to both the ice and benthic microalgal communities, many ice algal species found in the sediments were unhealthy and had probably originated in the ice. More taxonomic work needs to be done on this difficult group. Using existing techniques, it is difficult to adequately separate algal cells from the sediments, and cell counts are semi-quantitative at best.

F. Copepods were the dominant taxonomic group of zooplankton during the winter-spring period, and are numerically the most important species in the area during the entire year.

#### IX. Needs for further study

We have documented the development of the ice algal bloom, and the relative contributions of the ice algae, **phytoplankton**, and benthic **microalgae** to primary production during much of the winter-spring period, and have gone far in elucidating the interrelationships of these communities. However, several questions remain to be answered.

A. There is a <sup>gap</sup> in our knowledge of the crucial period following dissolution of the ice algal layer in early June, leading up to the spring **phytoplankton** bloom after breakup.

1. What is **the fate of** the ice algae once they leave the ice? Are they rapidly consumed by zooplankton? Do they sink to deeper water? Are they incorporated into the sediments? Are they so diluted in the water column that we **don't** collect them by conventional sampling methods? Or, do many of the cells die in the low salinity water during ice melt with relatively rapid dissolution of the silica valves?

2. **The** spring **phytoplankton** bloom is composed of different species from those found in the ice and water column during the winter, and occurs after the end of the ice algal bloom. **What** is the origin of these cells? Are spores present in the sediments during winter that are able to germinate in spring in response to some environmental factor? What factors control this bloom?

B. In assessing the contribution of ice algae to the primary production of the nearshore ecosystem, we have concentrated efforts in the winter-spring period. There is evidence, however, that an ice algal layer also occurs in the fall. A sample of bottom ice collected in November 1980 near Narwhal Island contained an algal concentration comparable to that found during the preceding spring ice algal bloom. **Does** production occur in the **fall**? **What** is the extent of the layer in fall, temporally and spatially? Is it a regular occurrence?

C. Small **microflagellates** < 6  $\mu\text{m}$  in diameter are present, often in high numbers, in the ice and water column throughout the year. Many of them do not appear to be photosynthetic, and it is possible that they utilize dissolved or particulate organic material as an energy source. These organisms may be an important food source for grazers, and their role in the food chain dynamics of the nearshore ecosystem should be investigated.

D. The benthic microalgae were not very important in the nearshore area during the winter-spring period. At Barrow, however, production in this community in summer is high. Does the same thing happen in the **near-shore** Beaufort Sea? Does a mat of **filamentous** diatoms form in summer? Is this mat utilized as a food source by invertebrates?

E. Zooplankton are present all year round. What happens to the populations **in** summer? When do individual species breed? How long are individual life cycle stages? Do life cycles take more than one year? What food sources-are **being** utilized? Do these sources change during the life cycle? During the year?

F. Perhaps the most critical need with respect to oil and gas development: what are the effects of oil, drilling muds, **and** other pollutants on the organisms that live in the ice, water column, and benthos? Would they be able to survive a major spill? Could they repopulate an area? How long would recruitment and repopulation take? How would the loss of primary producers at different times of the year affect consumers, **particu-**larly higher **trophic** levels?

X. Auxiliary material: References cited

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An Improved Chamber for in situ Measurement of Primary  
Productivity of Arctic Sea Ice Algae

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Schrader, G.C., R.A. Homer, and G.F. Smith. 1981. An improved chamber for in situ measurement of primary productivity of Arctic sea ice algae.

An incubation chamber was designed to measure rates of carbon uptake of **microalgae** growing on the underside of Arctic sea ice. SCUBA divers are used to place the chambers, which are secured to the ice with steel pins. The chambers were found to accommodate a wide range of ice conditions, and were superior to the core-liner type chambers used previously.

Key words: Arctic Ocean; Sea Ice Algae; Primary Productivity.

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An Improved Chamber for in situ Measurement of Primary Productivity of Arctic Sea Ice Algae<sup>1</sup>

The occurrence of algae growing in sea ice is a widespread phenomenon which has been documented in both Arctic (Apollonio 1961; Meguro et al. 1967; Homer 1976; Alexander 1980) and Antarctic regions (Bunt and Wood 1963; Bunt and Lee 1970; Hoshiai 1977). In the Antarctic, Meguro (1962) described a community which occurs in snow that has been flooded by seawater. Hoshiai (1977) reported algae growing in two layers within the ice: an upper layer formed during early ice formation, incorporating components of the fall phytoplankton bloom, and a bottom layer formed on the underside of the ice in spring. The bottom layer is by far the most developed in both Arctic and Antarctic regions, and has been termed the "epontic" community by Bunt and Wood (1963). This community consists primarily of pennate diatoms and flagellates living attached to ice crystals and in brine pockets and interstitial water between crystals.

In the Arctic, little or no growth occurs during the dark winter months, but in the spring increasing insolation triggers a bloom which produces a golden-brown layer several centimeters thick on the underside of the ice. This layer typically persists until early June when the ice begins to soften and melt, and the algae are washed from the ice. During this period ice algal productivity may be quite high. Clasby et al. (1973) reported maximum rates of  $4.56 \text{ mg C/m}^2 \cdot \text{hr}$  near Point Barrow, Alaska, with productivity in the ice usually far exceeding that of the underlying water column (Alexander et al. 1974). Although this high productivity is of relatively short duration, it is significant in that it extends the period of productivity in the Arctic by several months.

Attempts at measuring the rate of primary production of the ice algal community have employed a variety of strategies, all utilizing modifications of the  $^{14}\text{C}$  method of Steemann Nielsen (1952). One approach has been to obtain a sample of the under ice community by coring through the ice from the surface. The lower portion of the core containing ice algae may then be sectioned off and either taken to the laboratory for incubation (Homer and Alexander 1972; Alexander *et al.* 1974) or placed in a chamber, inoculated with isotope, and incubated in situ under the ice (MacLAREN MAREX 1979). Ice many meters thick may be sampled from the surface in this manner.

A similar approach was used by Andersen (1977) in a frozen lead in West Greenland where the ice did not exceed ca. 40 cm thickness. Blocks of ice were cut and removed, and clear plastic chambers attached to the underside. After inoculation the blocks were replaced and incubated in situ. This method is limited however, to ice of less than ca. 0.5m thickness.

There are certain problems inherent with surface operated collection techniques which are difficult to overcome. When coring devices are used the delicate structure of the ice algal layer is disturbed, resulting in partial loss of sample and interstitial water. In addition, thermal and light shock are difficult to avoid when bringing the samples to the surface, and ambient conditions are difficult to duplicate in the laboratory.

SCUBA divers were first used by Bunt (1963, 1973; Bunt and Lee 1970) to sample the ice algal community in the Antarctic. Samples were collected by forcing a Van Dorn sampler through the soft ice matrix; incubation was done in the laboratory. This method, however, did not overcome many of the problems encountered with surface coring devices.

The need for a good in situ method for work in the Arctic prompted Clasby *et al.* (1973) to design a combined sampler-incubation chamber which could be operated by SCUBA divers. The chamber was constructed of 4.8 cm diameter plexiglass core tube lining 4 cm in length. One end was closed off with a plexiglass plate fitted with a rubber septum,

and the top of the sampler was serrated to cut into the ice.

To place the chamber, a diver removed the septum, which allowed the water to evacuate, and screwed the sampler into the underside of the ice to a depth of 2 cm. The septum was then replaced and a syringe used to inoculate the chamber with  $^{14}\text{C}$ -bicarbonate solution. After an appropriate incubation period a heavy metal spatula was used to chip away ice from around the chamber and then sever the top of the core. The sample was retained in the chamber by a core cap. Dark uptake rates were determined in a darkened chamber that was capped and suspended from ice pitons immediately following inoculation. The chamber was also used to collect samples for chlorophyll, standing stock, nutrient and other analyses.

Alexander et al. (1974) compared rates of primary productivity of Arctic ice algae determined by both the diver operated technique and surface core-culture chamber techniques, and found significantly higher apparent rates of carbon uptake with the in situ method.

Although used successfully to measure primary productivity in sea ice near Point Barrow, Alaska (Clasby et al. 1973), we felt that the chamber should be redesigned to accommodate a greater range of ice conditions and to minimize sample loss during core extraction and capping.

Two new features were incorporated into the new chamber. The chamber was provided with a holder equipped with four threaded stainless steel pins adjusted to protrude approximately 2 cm from the chamber mouth (Fig. 1). The chamber could then be hammered into the ice where the pins would anchor it securely. In addition, a scraper was designed with a locking pin that fit into a guide in the holder. At the end of the incubation period, while the chamber is still anchored to the ice, the pin is started into the guide, and the core severed as the scraper is pushed into place, sealing the chamber mouth. The scraper is secured by a handle on the bottom of the holder which is screwed tightly against the pin. The chamber can then be returned to the surface with little sample loss. As an added precaution when

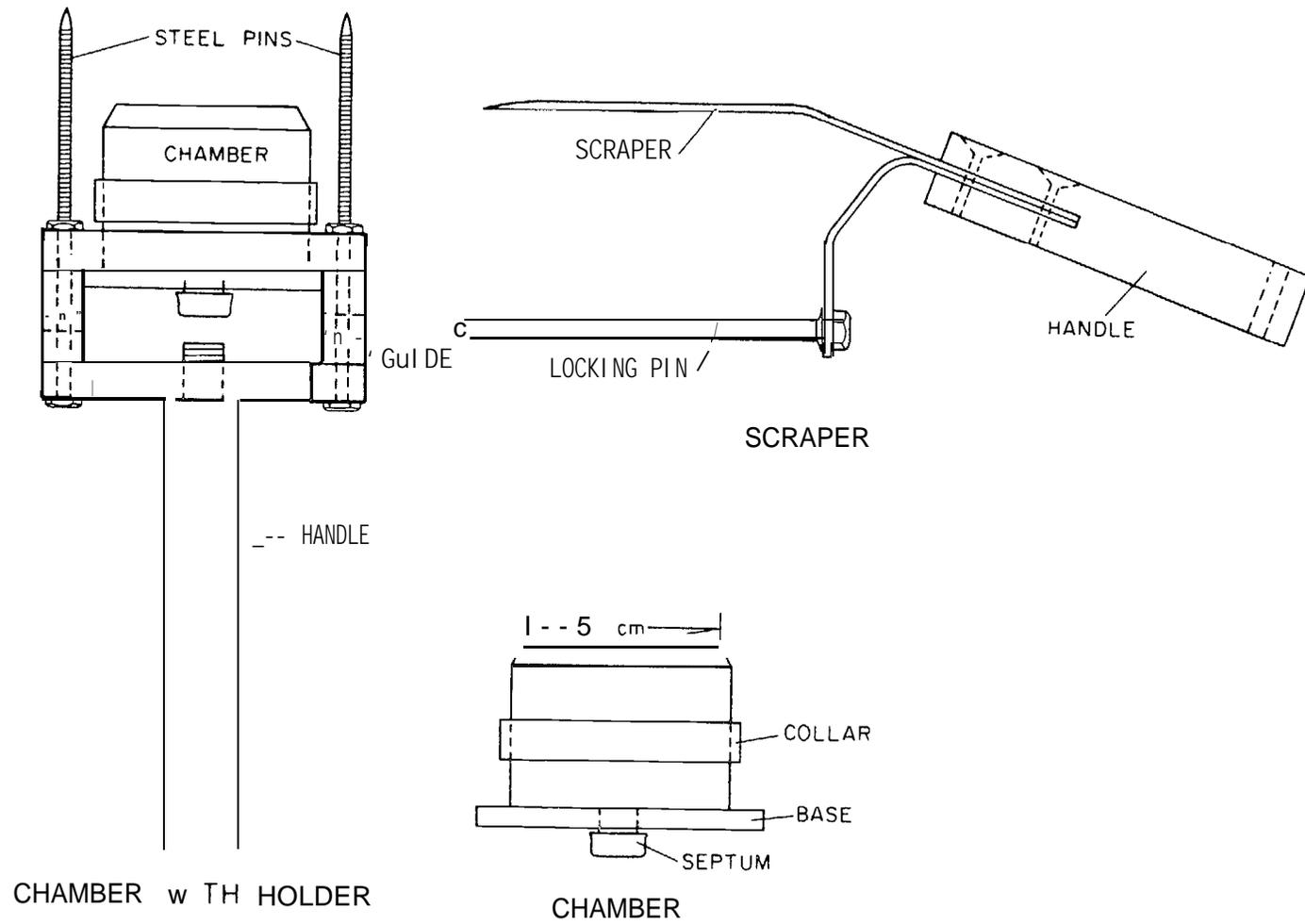


Fig . 1 Ice algal incubation chamber.

returning the chambers to the surface, the scraper is held tightly over the chamber mouth to prevent leakage.

To measure dark uptake, a darkened chamber is hammered into the ice and the scraper inserted to enclose the ice sample prior to injecting the isotope. This allows the chamber to remain **in place during** the incubation period. As the added weight of the scraper has a tendency to pull the sampler from the ice, a **donut-shaped float is** placed over the handle of dark chambers to provide additional security.

The chamber is constructed of 5 cm inside diameter clear Lexan plastic tubing 4.5 cm high. The upper edge is beveled and the bottom glued to a square plastic base drilled to accept a serum bottle septum. The chamber is placed in its holder by dropping the base through a square opening and rotating 45 degrees. The holder provides support for the base of the chamber, and a tight fitting plastic collar is slipped over the outside of the chamber to keep it in place. The base of the holder is open to allow access to the septum for inoculation with a syringe. In practice, the chamber is rarely removed from the holder except for maintenance.

The scraper is constructed from stainless steel, with the blade sharpened and tempered to increase durability. A Lexan handle is attached at a 30 degree angle to provide clearance for the diver's hand when scraping the flat undersurface of the ice.

The new chambers were **field** tested in spring 1980 at a station approximately 25 km offshore from Prudhoe Bay, Alaska (ms in prep.). The ice was approximately 1.7 m thick. A variety of conditions were encountered on the underside of the ice during the two months the station was occupied. In April, when the ice was still rapidly **accreting**, the algae were associated with a layer of hard vertical platelets several centimeters deep. By early June, when the ice began to soften, the algae had formed a "slush **layer**" overlying harder ice. The new samplers performed satisfactorily under all conditions. They remained in place well and divers did not observe sample loss during extraction.

At intervals throughout the study we attempted to compare rates of primary production measured by both the older core liner type chambers (Clasby et al. 1973) and our new chambers. We were unsuccessful because the older style chambers would not remain in place in spite of numerous attempts by the divers. This clearly demonstrates the superiority of the new design, as the older chambers were totally ineffective in the ice conditions encountered during this study. The failure of the core liner type chambers to function during our study was surprising as they had been used successfully near Point Barrow, only a few hundred kilometers to the west. This suggests that there may be considerable year to year or regional variation in under-ice conditions in the Arctic.

Our sampler appears capable of accommodating a wide range of ice conditions, the major limitation being the depth of the layer of unconsolidated ice. The sampler will penetrate approximately 4.5 cm of unconsolidated ice, and is limited by the height of the chamber. By lengthening the chamber, pins, and scraper assembly, this design should work well in ice several times this depth. It is recognized however, that this chamber would have limited usefulness in the Antarctic, where the unconsolidated layer may be 1 m thick (Bunt 1963). Individual ice crystals are frequently very large and the introduction of a chamber would tend to interfere seriously with the integrity of the ice matrix.

Although we feel that our in situ chamber offers an improvement over previous methods, several problems have yet to be overcome before we feel that we can adequately assess rates of primary production in Arctic sea ice. As the ice algal layer is often formed of a matrix of ice crystals, it is difficult to insure adequate mixing of the isotope throughout the sample. The addition of a stirring apparatus to the chamber may prove worthwhile. However, artificial mixing would tend to destroy gradients which probably exist within the ice matrix and could affect carbon uptake rates. Also, due to the porous nature of the ice, an unknown amount of label may diffuse from the chamber during incubation. An estimate of this loss could be obtained by determining the total amount of isotope recovered at the end of the incubation period.

An additional problem is encountered when an area is sampled repeatedly by SCUBA divers. Exhaust air from the **diver's** breathing apparatus collects on the bottom of the ice leaving "pockmarks" or "**craters**", and divers have observed a reduction in algal growth in these craters. The use of a diving apparatus which would exhaust air directly to the surface would alleviate this problem.

These experimental problems lead to an underestimation of primary productivity of the ice algal community. It is therefore suggested that all such reported productivity data be considered as minimum values.

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APPENDIX II

Appendix Table II-1. Surface weather observations. All measurements were taken at ea. 1100. Where no number is present data were not available.

Date	Temp ("c)		Wind		Weather	Cloud		Snow Depth (cm)	Ice Thickness (cm)
	Air	Water Sfc	Speed (kt)	Direction (° mag)		Type	Cover		
10 Apr	-22	-1.8	0		clear			5	
12	-19.5	-1.8	15	030	clear			5	
14	-18.2	-1.8	25	030	blowing snow			variable	
17	-15.2	-1.8	10-20	020	fog	broken		3	
19	-17.6	-1.8	20	020	clear			variable	
24	-14.7	-1.8	15-20	030	clear			5	169
28	- 9.4	-1.8	10-15	030	clear	stratus	10/10	2	
29	- 9.8	-1.8	10-15	040	clear	stratus	8/10	2-3	
2 May	- 8.5	-1.8	5	010	snow	stratus	10/10	6	
5	-11.0	-1.8	20	030	clear			3.5	
6	-11.5	-1.8	30	030	blowing snow			3	
8	-15.5	-1.8	20	030	clear	stratus/ cirrus	2/10	2	
15	- 6.0	-1.8	30	040	clear	stratus	10/10	3	
17	- 2.9	-1.8	20-30	050	clear	cirrus	3/10	2.5	176
19	- 7.5	-1.8	15	030	clear			2.5	
20	- 6.0	-1.8	5-10	030	snow	stratus	10/10	2	
22	- 6.2	-1.8	10-15	030	snow	stratus	10/10	variable	
24	- 2.0	-1.8	10-15	030	clear	stratus	10/10	2.5	
26	1.2	-1.8	20	035	clear	stratus	7/10	1	
29	0.0	-1.8	10-15	055	clear	stratus	5/10	0	
31	- 5.0	-1.8	15	030	clear	stratus	10/10	0	
2 Jun	1.0	-1.8	10	050	snow	stratus	6/10	0	178
3	- 0.5	-1.8	5	042	clear	stratus	6/10	0	
5	2.0	-1.8	0-5	090	rain	stratus	10/10	0	
7	2.0	-1.5	5	040	rain	stratus	10/10	0	
9	9.5	-1.5	0		clear		0/10	0	
11	9.5	0.0	0		clear	cirrus	3/10	0	

Appendix Table II-2. Concentration of **microflagellates** and diatoms in the ice and water column, Narwhal Island, spring 1980.

Date	0 m		7 m		Ice	
	Diatoms	Flagellates (Cells $\ell^{-1}$ )	Diatoms	Flagellates	Diatoms	Flagellates (Cells $m^{-2}$ )
Apr 10	3.4X10 <sup>4</sup>	2.0x10 <sup>5</sup>	2.5x10 <sup>3</sup>	6.0x10 <sup>4</sup>	1.7X10 <sup>8</sup>	5.8x10 <sup>7</sup>
12		1.9X10 <sup>5</sup>		1.3X10 <sup>5</sup>		
14	1.0X10 <sup>2</sup>	1.3X10 <sup>5</sup>	1.0x10 <sup>3</sup>	1.4X10 <sup>5</sup>	2.4x10 <sup>7</sup>	2.5x10 <sup>8</sup>
17	1.0X10 <sup>3</sup>	1.7X10 <sup>5</sup>	3.0X10 <sup>3</sup>	1.4X10 <sup>5</sup>	4.6x10 <sup>6</sup>	1.9X10 <sup>8</sup>
19	6.0x10 <sup>3</sup>	1.4X10 <sup>5</sup>	4.2x10 <sup>2</sup>	1.4X10 <sup>5</sup>	2.5x10 <sup>8</sup>	2.8x10 <sup>8</sup>
24	3.0X10 <sup>3</sup>	6.7x10 <sup>4</sup>	3.0X10 <sup>2</sup>	4.5X10 <sup>4</sup>	7.1X10 <sup>8</sup>	6.7x10 <sup>8</sup>
29	6.0x10 <sup>3</sup>	1.1X10 <sup>5</sup>	2.0X10 <sup>3</sup>	1.4X10 <sup>5</sup>	4.8x10 <sup>6</sup>	1.3X10 <sup>8</sup>
May 2	8.1x10 <sup>4</sup>	6.9x10 <sup>5</sup>	3.1X10 <sup>3</sup>	2.5x10 <sup>5</sup>	5.6x10 <sup>8</sup>	2.9x10 <sup>8</sup>
5	7.9X10 <sup>3</sup>	1.3X10 <sup>5</sup>	4.1X10 <sup>4</sup>	1.8x10 <sup>5</sup>	1.1x10 <sup>9</sup>	2.8x10 <sup>8</sup>
8	1.2X10 <sup>4</sup>	1.3X10 <sup>5</sup>	2.0X10 <sup>3</sup>	1.7X10 <sup>5</sup>	6.9x10 <sup>7</sup>	7.5X10 <sup>7</sup>
15	6.8X10 <sup>4</sup>	1.9X10 <sup>5</sup>	1.2X10 <sup>4</sup>	1.6x10 <sup>5</sup>	9.3X10 <sup>6</sup>	1.4X10 <sup>7</sup>
17	8.1x10 <sup>3</sup>	1.4X10 <sup>5</sup>	1.0X10 <sup>2</sup>	9.0X10 <sup>4</sup>		
20	2.5X10 <sup>4</sup>	1.5X10 <sup>5</sup>	3.0X10 <sup>3</sup>	1.9X10 <sup>4</sup>	1.6x10 <sup>8</sup>	7.9X10 <sup>7</sup>
22	3.3X10 <sup>4</sup>	1.2X10 <sup>5</sup>	1.9X10 <sup>4</sup>	4.8x10 <sup>4</sup>	7.9X10 <sup>8</sup>	5.8x10 <sup>8</sup>
24	1.7X10 <sup>4</sup>	1.5X10 <sup>5</sup>	6.0x10 <sup>3</sup>	7.4X10 <sup>4</sup>	8.2x10 <sup>8</sup>	5.0X10 <sup>8</sup>
26	1.4X10 <sup>4</sup>	1.1X10 <sup>5</sup>	1.0X10 <sup>3</sup>	2.9X10 <sup>4</sup>	1.0X10 <sup>9</sup>	7.9X10 <sup>8</sup>
29	1.8x10 <sup>4</sup>	1.0x10 <sup>5</sup>	2.0X10 <sup>3</sup>	1.0X10 <sup>4</sup>	8.5x10 <sup>8</sup>	7.5X10 <sup>8</sup>
31	8.0x10 <sup>3</sup>	6.0x10 <sup>4</sup>	1.0x10 <sup>4</sup>	1.3X10 <sup>4</sup>	1.2X10 <sup>9</sup>	2.0X10 <sup>9</sup>
Jun 2	1.5X10 <sup>4</sup>	9.0x10 <sup>4</sup>	3.0X10 <sup>3</sup>	2.7X10 <sup>4</sup>	8.5x10 <sup>8</sup>	9.2x10 <sup>8</sup>
5	3.6x10 <sup>4</sup>	2.3X10 <sup>4</sup>	6.0x10 <sup>3</sup>	2.3x10 <sup>3</sup>	6.7x10 <sup>8</sup>	9.9x10 <sup>8</sup>
7	5.9X10 <sup>4</sup>	1.3X10 <sup>5</sup>	8.0x10 <sup>3</sup>	7.0X10 <sup>3</sup>	6.6x10 <sup>8</sup>	1.6x10 <sup>9</sup>
9	2.4x10 <sup>4</sup>	6.6x10 <sup>4</sup>	3.0X10 <sup>3</sup>	7.0X10 <sup>3</sup>	1.1x10 <sup>9</sup>	1.0X10 <sup>9</sup>
11	1.6x10 <sup>5</sup>	1.5X10 <sup>5</sup>	3.0X10 <sup>4</sup>	6.8x10 <sup>4</sup>	7.0x10 <sup>6</sup>	8.7x10 <sup>6</sup>

Appendix Table II-3. Concentrations of diatoms in the ice, water column, and benthos, Narwhal Island, spring 1980.

Date	Ice	Benthos (Cells m <sup>-2</sup> )	Water	0 m (Cells l <sup>-1</sup> )	7 m
Apr 10	1.7X10 <sup>*</sup>		1.2x10 <sup>8</sup>	3.4X10 <sup>4</sup>	2.5x10 <sup>3</sup>
12					
14	2.4x10 <sup>7</sup>		3.9x10 <sup>6</sup>	1.0x10 <sup>2</sup>	1.0X10 <sup>3</sup>
17	4.6x10 <sup>6</sup>	1.3X10 <sup>9</sup>	1.4X10 <sup>7</sup>	1.0x10 <sup>3</sup>	3.0X10 <sup>3</sup>
19	2.5x10 <sup>8</sup>	2.7x10 <sup>8</sup>	2.2X10 <sup>7</sup>	6.0x10 <sup>3</sup>	4.2x10 <sup>2</sup>
24	7.1x10 <sup>8</sup>		1.2X10 <sup>7</sup>	3.0X10 <sup>3</sup>	3.0X10 <sup>2</sup>
29	4.8x10 <sup>6</sup>		2.8x10 <sup>7</sup>	6.0x10 <sup>3</sup>	2.0X10 <sup>3</sup>
May 2	5.6x10 <sup>B</sup>	9.0x10 <sup>8</sup>	2.9x10 <sup>8</sup>	8.1x10 <sup>4</sup>	3.1X10 <sup>3</sup>
5	1.1X10 <sup>9</sup>		2.1X10 <sup>7</sup>	7.9X10 <sup>3</sup>	4.1x10 <sup>4</sup>
8	6.9x10 <sup>7</sup>	3.0X10 <sup>*</sup>	4.9X10 <sup>7</sup>	1.2X10 <sup>4</sup>	2.0X10 <sup>3</sup>
15	9.3X10 <sup>6</sup>		2.8x10 <sup>8</sup>	6.8X10 <sup>4</sup>	1.2X10 <sup>4</sup>
17			2.1X10 <sup>7</sup>	8.1x10 <sup>3</sup>	1.0X10 <sup>2</sup>
20	1.6x10 <sup>8</sup>		9.8x10 <sup>7</sup>	2.5x10 <sup>4</sup>	3.0X10 <sup>3</sup>
22	7.9X10 <sup>8</sup>	3.0X10 <sup>9</sup>	1.8x10 <sup>8</sup>	3.3X10 <sup>4</sup>	1.9X10 <sup>4</sup>
24	8.2x10 <sup>8</sup>		8.1x10 <sup>7</sup>	1.7X10 <sup>4</sup>	6.0x10 <sup>3</sup>
26	1.0x10 <sup>9</sup>		5.3X10 <sup>7</sup>	1.4X10 <sup>4</sup>	1.0X10 <sup>3</sup>
29	8.5x10 <sup>8</sup>	4.0x10 <sup>8</sup>	7.0x10 <sup>7</sup>	1.8x10 <sup>4</sup>	2.0X10 <sup>3</sup>
31	1.2x10 <sup>9</sup>		6.3x10 <sup>7</sup>	8.0x10 <sup>3</sup>	1.0x10 <sup>4</sup>
Jun 2	8.5x10 <sup>8</sup>		6.3x10 <sup>7</sup>	1.5X10 <sup>4</sup>	3.0X10 <sup>3</sup>
5	6.7x10 <sup>8</sup>	8.0x10 <sup>8</sup>	1.5X10 <sup>8</sup>	3.6x10 <sup>4</sup>	6.0x10 <sup>3</sup>
7	6.6X10 <sup>8</sup>		2.3x10 <sup>8</sup>	5.9X10 <sup>4</sup>	8.0x10 <sup>3</sup>
9	1.1X10 <sup>9</sup>		9.5X10 <sup>7</sup>	2.4x10 <sup>4</sup>	3.0X10 <sup>3</sup>
11	7.0X10 <sup>6</sup>		6.7x10 <sup>8</sup>	1.6x10 <sup>5</sup>	3.0X10 <sup>4</sup>

Appendix Table II-4. Snow depth, percent surface light, and extinction coefficient (k) of ice determined from transects through snow drifts, Narwhal Island, spring 1980. The extinction coefficient (k) was determined after the ice algae layer was removed.

Snow Depth (cm)	Percent Surface Ice	Light O m	Extinction Coefficient kite (m <sup>-1</sup> )
Drift in lee of tent shelter; 28 Apr			
2.0	2.29	1.63	0.94
1.5	2.29	1.74	0.95
2.5	2.29	1.66	0.94
3.0	1.95	1.63	0.98
3.0	2.00	1.37	0.97
2.8	1.95	1.37	0.98
2.8	1.84	1.21	0.99
2.5	1.47	1.18	1.05
2.8	1.26	0.92	1.09
3.0	0.76	0.71	1.21
5.5	0.63	0.47	1.24
5.5	0.45	0.39	1.32
4.0	0.34	0.29	1.40
6.0	0.24	0.18	1.47
19.0	0.13	0.13	1.59
30.0	0.06	0.06	1.59
45.0	0.04	0.04	1.57
47.0	0.02	0.02	1.69
54.0	0.02	0.02	1.64
54.0	0.01	0.01	1.77
Drift in lee of tent shelter; 6 May			
2.0	0.88	0.69	1.18
1.0	1.20	0.76	1.11
2.0	1.20	0.92	1.10
2.0	0.92	0.74	1.17
2.0	1.27	0.64	1.09
2.0	1.43	0.69	1.06
2.0	1.29	0.74	1.09
2.0	1.09	0.70	1.13
2.0	0.58	0.22	1.29
2.0	0.66	0.37	1.25
3.0	0.50	0.28	1.31
4.5	0.41	0.23	1.35
6.0	0.18	0.14	1.54
8.0	0.10	0.09	1.67
18.0	0.07	0.06	1.66
24.0	0.03	0.03	1.80
32.0	0.02	0.02	1.81
36.0	0.01	0.01	1.92
44.0	0.01	0.01	1.85
46.0	< 0.01	< 0.01	

Appendix Table II-4. (cent. )

Snow Depth (cm)	Percent Surface Ice	Light O m	Extinction Coefficient kite ( $m^{-1}$ )
Drift in lee of tent shelter; 19 May			
0.5	1.27	0.55	1.10
0.5	1.59	0.64	1.04
1.5	1.40	0.64	1.07
1.5	1.37	0.66	1.07
2.0	0.92	0.57	1.17
2.0	1.05	0.54	1.14
2.0	1.11	0.45	1.12
1.5	1.30	0.55	1.09
2.0	0.93	0.51	1.17
2.0	0.85	0.39	1.19
3.0	0.50	0.26	1.31
4.0	0.35	0.24	1.40
5.5	0.23	0.17	1.49
12.5	0.15	0.12	1.53
20.0	0.10	0.09	1.56
26.0	0.05	0.05	1.92
28.0	0.03	0.03	1.76
39.0	0.02	0.02	1.75
36.0	0.01	0.01	1.92
37.0	0.01	0.01	1.91
Drift in lee of tent shelter; 3 Jun			
0.0	1.92	0.83	1.00
0.0	2.14	0.86	0.97
0.0	2.43	0.95	0.94
0.0	1.90	1.08	1.00
0.0	2.14	0.63	0.97
0.0	1.66	0.66	1.03
0.0	1.66	0.47	1.03
0.0	2.14	0.50	0.97
0.25	2.08	0.47	0.98
0.50	0.90	0.45	1.19
2.5	0.83	0.25	1.19
3.5	0.65	0.30	1.25
6.5	0.41	0.20	1.34
13.0	0.30	0.21	1.36
16.0	0.25	0.16	1.38
19.0	0.13	0.11	1.51
24.0	0.11	0.10	1.51
23.0	0.08	0.06	1.59
30.0	0.05	0.04	1.63
31.0	0.04	0.04	1.67

Appendix Table II-4. (cent. )

Snow Depth (cm)	Percent Ice	Surface Light 0 m	Extinction Coefficient $k_{ice} (m^{-1})$
Study area windward of tent shelter; 17 May			
2.0	2.30	1.22	0.92
2.0	2.10	1.30	0.94
2.0	2.10	1.08	0.94
2.0	1.65	0.85	1.00
2.0	2.04	0.82	0.95
2.0	1.81	1.05	0.98
2.0	1.40	0.74	1.04
2.0	0.94	0.64	1.14
2.0	0.82	0.47	1.17
2.0	0.77	0.45	1.19
2.5	1.05	0.60	1.11
2.5	0.94	0.48	1.14
3.0	0.78	0.53	1.18
7.0	0.60	0.30	1.21
3.0	0.51	0.26	1.28
3.0	0.68	0.34	1.21
3.0	0.57	0.27	1.25
5.5	0.52	0.24	1.26
10.0	0.23	0.14	1.42
20.0	0.10	0.07	1.53
Study area windward of tent shelter; 3 Jun			
0.0	3.11	1.87	0.88
0.0	3.14	1.43	0.87
0.0	2.67	1.90	0.91
0.0	2.43	1.48	0.95
0.0	2.44	0.92	0.95
0.0	2.64	1.54	0.92
0.0	2.25	0.80	0.96
0.0	1.58	0.47	1.06
0.0	1.52	0.30	1.05
0.0	1.84	0.50	1.02
0.0	1.60	0.38	1.06
0.0	1.60	0.56	1.06
0.0	1.28	0.51	1.11
0.5	0.86	0.29	1.22
5.0	0.83	0.21	1.20
3.0	0.50	0.21	1.18
4.0	0.62	0.26	1.25
7.0	0.60	0.18	1.29
13.0	0.47	0.17	1.26
20.0	0.15	0.09	1.47