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Effects of Oil and Chemically Treated Oil on Primary Productivity of High Arctic Ice Algae Studied *in situ*

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ABSTRACT. Control data on the ice algal bloom at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982 were typical of those at other arctic locations. Ice algae were dominated by pennate diatoms (80% of total cells), particularly *Nitzschia grunowii* (55%) and *N. frigida* (15%). In various locations and sampling periods, cell densities ranged from 1.7-384.7 $\times 10^7$ cells·m^{-2}, and chlorophyll *a* concentrations ranged from 3.4-16.7 mg·m^{-2}; both increased over the study period. Mean productivity rates based on particulate radiocarbon fixed were from near zero to 2.95 mg C·m^{-2}·h^{-1}. Dissolved organic radiocarbon concentrations were almost always higher than particulate radiocarbon concentrations, probably because of cell rupture. Total (dissolved + particulate) productivity rates were up to 12.7 mg C·m^{-2}·h^{-1}, with an overall mean of 4.4 mg C·m^{-2}·h^{-1} in control samples. Productivity and productivity per unit chlorophyll increased during May and decreased slightly by 1-2 June.

Undisturbed, enclosed areas of the under-ice surface were treated with oil on 23-24 May. Dispersed oil (Venezuela Lagomedio crude + Corexit 9527, BP CTD, or BP 1100 WD) was in contact with the ice for 5 h, whereas untreated oil and solidified oil (BP treatment) remained in the enclosures for the duration of the study (12 days post-treatment). Sampling was carried out in areas where oil contacted the ice and moved away or in areas near oil that remained in contact with the under-ice surface. Five hours after treatment, oil concentrations in the water within the enclosures were similar (0.15-0.28 ppm) in untreated oil, solidified oil and control enclosures. In contrast, dispersed oil concentrations were 5.8-36.5 ppm. No adverse effects of any oil treatment on ice algae were detected in analyses of group composition, cell densities, chlorophyll *a* concentrations, productivity, productivity/chlorophyll or ratios calculated to standardize for light effects. Untreated and solidified oil may have stimulated ice algal growth and productivity near (but not in) the oiled areas.

Key words: Arctic, ice algae, productivity, oil effects, dispersed oil effects, solidified oil effects, Baffin Island

RÉSUMÉ. Les données de contrôle sur le développement des algues glaciaires au cap Hatt, au nord de l'île Baffin, relevées entre le 18 mai et le 2 juin 1982, ont été semblables à celles obtenues dans d'autres régions arctiques. Les algues glaciaires étaient en grande partie composées de diatomées pennées (80% des cellules au total), surtout de *Nitzschia grunowii* (55%) et de *N. frigida* (15%). A plusieurs endroits et durant plusieurs périodes d'échantillonnage, les densités des cellules allaient de 1,7 à 384,7 $\times 10^7$ cellules·m^{-2}, et les concentrations de chlorophylle *a* allaient de 3,4 à 16,7 mg·m^{-2}; ces deux densités ont augmenté au cours de la durée de l'étude. Les taux moyens de productivité basés sur le radiocarbone fixé sous forme de particules, allaient de près de 0 à 2,95 mg C·m^{-2}·h^{-1}. Les concentrations de radiocarbone organique dissous étaient presque toujours plus élevées que celles du radiocarbone sous forme de particules, probablement à cause de la rupture cellulaire. La somme des taux de productivité (dissous et sous forme de particules) atteignait 12,7 mg C·m^{-2}·h^{-1}, avec une moyenne générale de 4,4 mg C·m^{-2}·h^{-1} dans les échantillons témoins. La productivité totale et la productivité par unité de chlorophylle ont augmenté durant mai et avaient diminué légèrement au 1er ou au 2 juin.

Des endroits non perturbés et fermés de la surface de la glace immergée ont été traités avec du pétrole les 23 et 24 mai. Du pétrole dispersé (Lagomedio du Vénézuéla avec Corexit 9527, BP CTD ou BP 1100 WD) a été en contact avec la glace pendant 5 heurs, tandis que du pétrole non traité et du pétrole solidifié (traitement BP) sont restés dans ces zones fermées pendant toute la durée de l'étude, soit 12 jours après le traitement. Des échantillons ont été relevés dans des endroits où le pétrole avait touché la glace et s'était déplacé, et dans des endroits proches de là où le pétrole était resté en contact avec la surface de la glace immergée. Cinq heures après le traitement, les concentrations de pétrole dans l'eau à l'intérieur des endroits fermés étaient semblables (de 0,15 à 0,28 p.p.m.) dans les zones fermées exposées au pétrole non traité, au pétrole solidifié et dans les zones témoins. Par contre, les concentrations de pétrole dispersé étaient de 5,8 à 36,5 p.p.m. Aucun effet négatif de l'un des traitements du pétrole sur les algues glaciaires n'a été détecté dans les analyses de composition des groupes, de densités cellulaires, de concentrations de chlorophylle *a*, de productivité, de productivité par unité de chlorophylle, ou de rapports calculés pour normaliser les effets de la lumière. Les pétroles non traité et solidifié pourraient avoir stimulé la croissance des algues glaciaires et leur productivité près des zones traitées au pétrole, mais pas à l'intérieur de celles-ci.

Mots clés: arctique, algues glaciaires, productivité, effets dus au pétrole, effets dus au pétrole dispersé, effets dus au pétrole solidifié, île Baffin

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INTRODUCTION

In spring, a dense growth or bloom of microalgae occurs on and in the soft bottom layer of arctic sea ice. This algal layer begins to develop in April and the bloom peaks in May, after which time increased radiation and selective absorption by plant pigments cause the layer to disintegrate (Horner, 1976, 1977). Productivity of ice algae during the relatively short bloom in April and May can be quite high. The bloom has been estimated to provide between 6 and 33% of the total annual primary production in various arctic locations (Alexander, 1974; Horner *et al.*, 1974; Welch and Kalff, 1975). In addition, this bloom is important because its production occurs before there is significant production by planktonic and benthic algae during the open water season (Apollonio, 1965). Thus, ice algal production is available to herbivores earlier in the season than is planktonic production (Dunbar, 1968). This availability is further enhanced by the concentration of ice algae on the bottom of the ice and, near the end of the bloom, by their occurrence as macroscopic "detrital" masses on the under-ice surface and in the water column (Cross, 1982a).

Reviews of early published research on under-ice biota in the Arctic are given by Horner (1976, 1977). Most of the more recent studies describe ice algal species composition and biomass; few document primary productivity. Few studies have used scuba techniques, which overcome many of the difficulties and sources of error associated with sampling and carrying out experiments on the ice bottom.

In the event of a subsea oil blowout under seasonal ice cover, large quantities of oil are likely to accumulate in the under-ice habitat. During ice break-up in late spring/early summer, oil from a marine oil spill or blowout may be transported under fast ice edges by currents. Various chemical countermeasures are under consideration for oil spills in ice-covered waters. Effects

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of chemically treated and untreated oil on under-ice biota should be understood before countermeasures are chosen. Productivity and biomass of phytoplankton under oiled ice have been reported (e.g., Adams 1975), and effects of oil and dispersed oil on arctic phytoplankton and ice algae have been tested in laboratories (Hsiao, 1978; Van Baalen and O'Donnell, 1984). To my knowledge, the only previous *in situ* study of oil effects on ice algae is that of Cross (1982b). That study, carried out at Cape Hatt, Baffin Island, in May 1981, concerned short-term effects of oil and dispersed oil on ice algal productivity and associated variables. The results of that study were used in designing the present one, which was carried out at the same location in May 1982.

In this study, I attempted to create realistic scenarios for the impingement of oil onto the under-ice surface: low concentrations of dispersed oil contacting the ice for a short period of time, and untreated oil and solidified oil remaining in place on the under-ice surface. The productivity studies described here address the effects of oil, solidified oil and dispersed oil (three different chemical dispersants) on ice algal productivity, biomass, density and group composition. By using spatial and temporal controls I examined the initial impact on and subsequent recovery of under-ice algae subjected to a single application of these treatments.

The papers in this volume report results of the Baffin Island Oil Spill (BIOS) Project, which provided administrative and logistic support for the present study (see Acknowledgements). The BIOS Project assessed the use of chemical dispersants on an oil slick in arctic nearshore waters by comparing the fate and effects of dispersed oil with those resulting from the option of allowing the untreated oil slick to contact the beach and be removed by natural processes. The effectiveness of various shoreline cleanup techniques was also evaluated in separate study areas. Sergy and Blackall (1987) summarize the rationale, design and overall results of the BIOS Project.

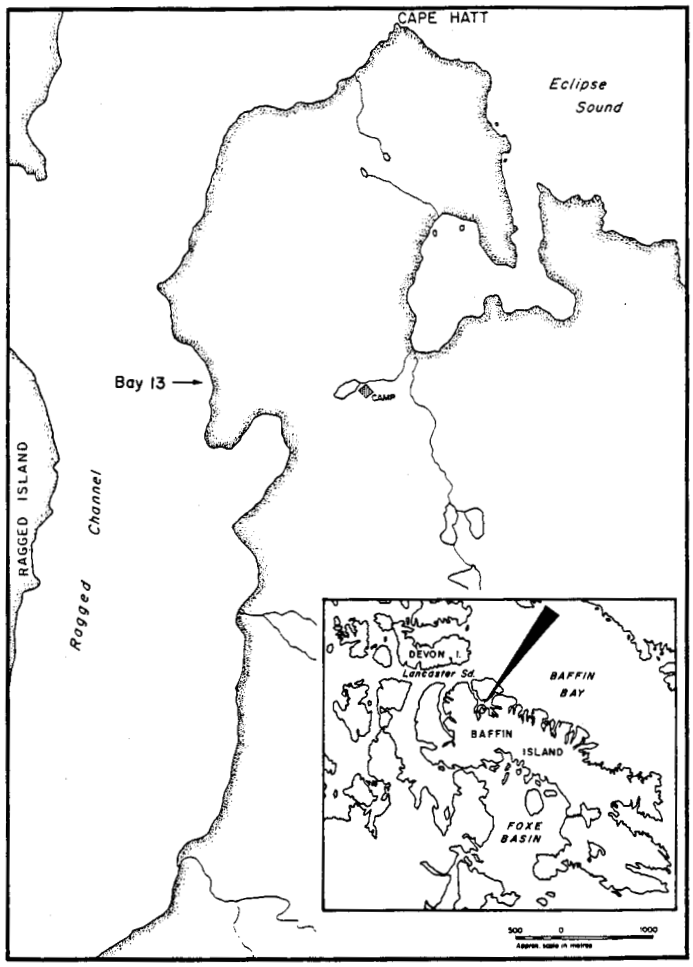

FIG. 1. BIOS site at Cape Hatt, northern Baffin Island (72°27'N, 79°51'W), showing the location of the study bay.

METHODS

Field Procedures

Field studies were carried out during 14 May-2 June 1982 from the BIOS (Baffin Island Oil Spill) Project base camp located at Cape Hatt, Baffin Island (72°27'N, 79°51'W). The study area consisted of a shallow embayment (Bay 13) in Ragged Channel, some 3 km to the north of the BIOS Project study bays (Fig. 1). All under-ice sampling and experimental work was carried out by scuba divers working through a hole in the ice over a water depth of 10 m and about 200 m from shore.

Under-ice algae were treated *in situ* with crude oil (Venezuela Lagomedio), solidified oil (BP treatment; see McGibbon *et al.*, 1982), oil dispersed with three different chemical dispersants (Corexit 9527, BP 1100 WD and BP CTD) and no oil (control). Each treatment was applied to the under-ice surface within buoyant plexiglass enclosures 1.2 m in diameter and 30 cm in depth (365 *l* in volume). High-density foam collars held the enclosures in contact with the under-ice surface. There were two enclosures for each of the six treatments; one set of six enclosures was established under the ice at each of two locations (Locations 1 and 2) separated by approximately 30 m.

Each oil-treated enclosure received 36.5 ml of oil, for a nominal concentration of 100 ppm if the oil was evenly dispersed. Oil and dispersants (10:1 ratio) were mixed with seawater in 9 *l* air-pressurized fire extinguishers. Dispersed oil, untreated oil and water (control and solidified oil treatments) were introduced from the extinguishers into the enclosures. In this way, any disturbance of the under-ice surface that resulted from the use of fire extinguishers was similar for all treatments. Solidified oil was prepared at the surface, transferred to a polyethylene bag and passively introduced into the enclosure after the control injection of water. The bottom of each enclosure was covered by polyethylene sheeting only during the application of treatments. Dispersed oil was contained within the enclosures for a period of 4-5 h and then the bottom sheet was removed; control, oil and solidified oil enclosures remained covered during the release of the dispersed oil to avoid cross-contamination, and then covers were removed. During the exposure period, water within the dispersed oil enclosures appeared very murky, whereas that in the other enclosures appeared clear. Untreated oil and solidified oil remained in localized areas (less than 10% of the under-ice surface) within the enclosures throughout the study (diver observations). Just before the covers were removed from enclosures, water samples from each enclosure were collected in 50 ml polypropylene syringes and frozen for hydrocarbon analysis.

Sampling was carried out within the enclosures during five periods, each consisting of 2 d: 18-19, 21-22, 26-27 and 28-29 May and 1-2 June. Treatments were applied on 23-34 May. In each of these 2 d periods, Locations 1 and 2 were sampled (or

treated) on the first and second day respectively. In untreated and solidified oil enclosures, sampling was carried out within the enclosures, but not directly in the oiled areas, which covered less than 10% of the ice within the enclosures. It is reasonable to assume that most biological processes would cease directly above a pool of oil or a mass of chemically solidified oil, and hence the areas sampled were areas where oil contacted the ice, but moved away, or areas in near proximity to untreated or solidified oil.

Productivity of under-ice algae was determined by a modification of the standard ^{14}C light and dark bottle technique (Strickland and Parsons, 1972). The "bottles" in this case were cylindrical plexiglass chambers with diameter 10 cm and length 15.3 cm (volume = 1202 cc). The chambers, which were open at one end, were inserted about 1-2 cm into the soft bottom layer of ice within the enclosures, and ^{14}C-sodium bicarbonate (New England Nuclear Corp.) with a specific activity of 53 mCi·mmol^{-1} was injected to yield a final concentration of 75.9 $\mu Ci \cdot l^{-1}$. Incubations began between 1100 and 1200 h and continued for 2-2.5 h. At the end of the incubation periods, entrapped ice was severed at the tops of the chambers, the chambers were capped and 1 ml of formaldehyde solution (37% w/w) was injected into each. This use of formalin likely caused cell rupture, the effects of which are discussed in a later section. Incubation chambers were returned to the field laboratory within 1-2 h after the incubation period and processed within 8 h.

During each sampling period, three replicate light chambers and one dark chamber were used to incubate ice (+ water) samples in each enclosure. Because each treatment was applied to two enclosures, there was a total of six light and two dark chambers for each of the six treatments (48 samples) in each of the five 2 d sampling periods. To determine the contribution of algae in the water to the above ice (+ water) incubations, water samples were also collected immediately beneath the ice within the enclosures. One light and one dark chamber were incubated for each treatment (12 samples) in each period. Separate samples of ice (+ water) were collected in the same way and returned immediately to the field laboratory for the determination of salinity, alkalinity and ambient inorganic nutrient concentrations. Salinity and alkalinity were measured immediately, and nutrient samples were preserved with 1 or 2 drops of chloroform (samples for phosphate and ammonium analyses) or 2 drops of concentrated sulphuric acid (samples for nitrate-nitrite analysis) before freezing.

Light was measured with an underwater irradiometer (Kahlsico model 268 WA310) below the layer of ice algae and above the algal layer (after scraping this layer away) in each enclosure at the beginning of each incubation. Measurements above and below the ice algal layer were averaged for subsequent calculations. Simultaneous measurements above the ice were made with a surface cell so that percent transmission through the ice could be calculated. A recording pyranometer (Kipp and Zonen, model CM-6) located 2 km away recorded incoming radiation ($W \cdot m^{-2}$) during the study period. *In situ* radiation was calculated as the amount of surface radiation during the incubation period ($W\text{-}h \cdot m^{-2}$) multiplied by percent transmission.

Laboratory Procedures

Field Laboratory: Actual sample volumes from incubation chambers varied to a maximum of 1350 ml and were sometimes very low because a few chambers leaked during transport to the laboratory. There was, however, no way in which one sample could have contaminated another. Because incubations were carried out *in situ*, leakage of ^{14}C from the chambers during incubations likely was minimal. Data from chambers where actual volume was <1100 ml (26 of 240 ice samples; 13 of 60 water samples) were not included in the analyses. The nominal chamber volume of 1200 ml was used in calculations for all chambers. Ice in samples from incubation chambers was allowed to melt at room temperature. Samples were then stirred thoroughly and subsampled for particulate radiocarbon (100 ml), dissolved organic radiocarbon (40 ml), chlorophyll *a* (50 ml) and density/species (400 ml) determinations. Particulate radiocarbon and chlorophyll subsamples were filtered through 0.45 μm Metricel cellulose triacetate filters (Gelman Sciences, Inc.) under a vacuum pressure of 200 mm Hg; dissolved organic radiocarbon subsamples were filtered through 0.45 μm silver filters (Selas Corp.) under a vacuum pressure of 120 mm Hg. The use of two different vacuum pressures introduced error that is discussed briefly in a later section. After particulate radiocarbon subsamples were filtered, the filters were rinsed twice with 15 ml filtered seawater and placed in 1 ml Cellusolve (BDH Chemicals Canada Ltd.) in 20 ml borosilicate glass scintillation vials (New England Nuclear Corp.). After the filters dissolved, 10 ml Aquasol (New England Nuclear Corp.) was added and the vials were capped tightly. For dissolved organic radiocarbon subsamples, the first 20 ml filtrate was discarded, and the second 20 ml filtrate was frozen in scintillation vials. For chlorophyll subsamples, a few drops of magnesium carbonate suspension were added at the end of filtration. The filters were folded in half, placed individually in glassine envelopes and frozen in plastic bags containing silica gel. Subsamples for taxonomic work were preserved in 3% formalin.

Carbonate alkalinity was calculated according to the methods of Strickland and Parsons (1972). A Fisher Accumet pH meter (model 630, accuracy ± 0.02 pH) was used to measure pH, and salinity was calculated from Knudsen tables using temperature and specific gravity measurements obtained with a hydrometer (Fisher, 1.000-1.070).

Permanent Laboratory: All measurements of nutrient and chlorophyll *a* concentrations and all radiometric procedures including the preparation of stock solutions were conducted at the Arctic Biological Station, Ste-Anne-de-Bellevue, Quebec. Orthophosphate (PO_4) and nitrate (NO_3) concentrations were determined on thawed samples using a Technicon Auto-Analyzer II continuous flow system and Technicon analysis procedures described in Bunch *et al.* (1985). Ammonia (NH_3) concentrations were determined according to the procedures of Dal Pont *et al.* (1974). Chlorophyll *a* was measured by the spectrophotometric procedure described in Strickland and Parsons (1972) using the equation of Jeffrey and Humphrey (1975). To determine productivity, ^{14}C radioactivity was measured using a Nuclear Chicago Isocap 300 scintillation counter. Dissolved organic radiocarbon samples were prepared for scintillation counting by acidification of a 10 ml portion of 20 ml filtrate to pH 2 and removal of $H^{14}CO_3$ in a gas stream (N_2, 30 min). The sample was then added to 10 ml Aquasol (New England Nuclear Corp.) and the resulting gel was counted as above. Counting inefficiencies were corrected by using the channel ratios method.

Microalgae (subsamples of 5 ml) were identified and enumerated using the inverted microscope method with magnifications to 625X. Normally, 2.5-10% of the settling chamber was scanned for abundant species and 50% was scanned for others.

Numbers of ice algae enumerated were converted to cells·l^{-1}. Each diatom, dinoflagellate and *Dinobryon* cell was counted as an individual, whereas each colony (except for *Dinobryon*) and filament of other groups was counted as one individual. Microalgae were identified to species whenever possible.

Oil concentrations were measured by ultraviolet fluorescence (UV/F) analysis using a Turner Designs Fluorometer. Prior to analysis, each frozen water sample was thawed, placed in a 125 ml separatory funnel and extracted twice with 10 ml hexane. The hexane extract was dried over anhydrous Na_2SO_4 and combined with a third 10 ml hexane that had been used to extract any remaining oil from the empty 50 ml polypropylene syringe used to collect the sample.

Data Analysis and Study Design

Data were analyzed with two- and three-factor analyses of variance (ANOVA), using the SAS general linear models (GLM) program (Helwig and Council, 1979). Variables analyzed included productivity, chlorophyll *a*, microalgal densities and ratios of productivity to chlorophyll *a*, chlorophyll *a* to percent transmission and productivity to *in situ* light.

To determine whether oil had an effect, temporal changes in the six enclosures and two locations were compared using three-factor (period, treatment, location) ANOVA, but significant three-way interactions necessitated the use of two-factor (period, treatment) ANOVA for each of the two locations. In statistical terms, a significant interaction between spatial and temporal effects indicated a possible oil effect (see Green, 1979). Such an interaction would occur when temporal change in the variable(s) was inconsistent among the enclosures, each of which received a different oil treatment (including no oil). Because factors other than the treatment (e.g., snow cover) could also lead to significant interaction effects, it was necessary to examine the data (e.g., to compare oil treatments with the controls) in order to make conclusions about oil effects. Because each treatment was replicated in a separate location (see Hurlbert, 1984), a comparison of results in the two locations was also used in evaluating possible oil effects.

RESULTS

Environmental Conditions

General information on the biology of the study area can be found in Snow *et al.* (1987). The under-ice surface was smooth and relatively flat, with shallow hummocks and ridges. Ice thickness was 135 cm at the entry hole. Snow depths on 3 June 1982 were 9.8 ± s.d. 1.7 cm (n = 14) and 18.2 ± 7.4 cm (n = 30) in Locations 1 and 2 respectively. The site was selected within Bay 13 on 7 May, with low and even snow depth (~10 cm) and 10 m water depth as the criteria. Differences in snow cover between locations were the result of high winds, snowfall and drifting snow on 12 and 13 May; snow cover was higher and more variable over Location 2, which was in the lee of two tents during the period of high winds. The amount of light penetrating the snow and ice during the experiments varied both spatially (primarily because of variable snow cover) and temporally. Temporal variation, within and among days, resulted from changes in cloud conditions and in solar elevation. *In situ* radiation during incubations varied among enclosures and periods by almost an order of magnitude.

Salinity of ice (+ water) samples ranged from 30.1-32.4‰; no consistent differences were apparent among days (18 May-1 June). Snow melt began near the end of May, but no obvious effects were observed under the ice. Ambient (pre-incubation) nutrient samples were collected in duplicate on 18, 19, 27 and 28 May and 1 June. Phosphate concentrations were 1.25-1.90 μmol·l^{-1}, nitrate concentrations were 3.04-10.23 μmol·l^{-1} and ammonia concentrations were 0.65-2.47 μmol·l^{-1}.

Phytoplankton Biomass and Productivity

Biomass (as estimated by chlorophyll *a* concentration) and productivity were very low in the water immediately beneath the ice. Mean concentration of chlorophyll *a* in control water samples was 1.93 ± s.d. 3.14 mg·m^{-3} (n = 24). The mean concentration of algal cells in near-ice water was $1.3 \pm 0.7 \times 10^4$ cells·l^{-1} (n = 17), and dominance was shared by pennate diatoms (48%) and microflagellates (45%). After correction for dilution (sampled ice depth = 1-2 cm; chamber depth = 15 cm), algal concentrations per unit volume were lower in the water than in the ice by 2-3 orders of magnitude. Thus, algae in control ice (+ water) samples can be assumed to be almost entirely from the ice.

Productivity in the near-ice water was also low; indeed, after dark ^{14}C uptake was subtracted from light ^{14}C fixation, net productivity values for most water samples were slightly negative. The mean uptake rate of radiocarbon in dark chambers was 0.29 ± 0.26 mg C·m^{-3}·h^{-1} (n = 11 controls), and the mean net productivity rate (light minus dark) was –0.0002 ± 0.2885 mg C·m^{-3}·h^{-1} (n = 13 controls). There was no significant difference ($P>0.5$) between light and dark radiocarbon uptake (paired t-test on scintillation counts for nine pairs of chambers; t = 0.20, $P>0.5$). Thus, productivity in control ice (+ water) samples can be assumed to be entirely from the ice.

Ice Algal Composition and Distribution

Major groups of microalgae were enumerated in a total of 174 ice (+ water) samples (including 83 controls), and species were identified and counted in 72 of these samples (32 controls). In contrast with samples of near-ice water, samples containing the bottom 1-2 cm layer of ice were overwhelmingly dominated by pennate diatoms (89% of algal cells in 83 control samples). A total of 59 species or varieties of microalgae was identified, and at least another 17 distinct but unidentified species were found. Of the 76 species, 61 were pennate diatoms (Table 1).

Nitzschia grunowii was the dominant species in 30 of 32 control samples and constituted an average of 54.8% of total algal numbers in those samples. *Nitzschia frigida* was dominant in 2 samples and ranked second in most of the remainder of the 32 samples. It constituted an average of 15.2% of total cells in 32 control samples.

Microalgae were relatively evenly distributed on a small scale (i.e., within the 1.2 m^2 enclosures); the standard deviation was usually much less than the mean (Table 2). Spatial variation on a larger scale (among enclosures separated by ~1-20 m) and temporal variation (among 5 sampling periods within the period 18 May-2 June 1982) were considerable: total microalgal densities in control samples ranged from 1.7 to 384.7 × 10^7 cells·m^{-2} (Table 2). In general, cell densities increased throughout the study period.

Ice Algal Biomass

The distribution of chlorophyll *a* in the bottom layer of ice,

TABLE 1. Genera and species of microalgae found in diver-collected ice cores[a] from Cape Hatt, Baffin Island, during 18 May-2 June 1982[b]

- Bacillariophyceae
  - Centrales[c]
    - *Chaetoceros*[c]
      - *C. compressus* Lauder
      - *C. karianus* Grunow in Cleve *et* Grunow
      - *C. septentrionalis* Östrup
      - *C. simplex* Ostenfeld
    - *Coscinodiscus*[c]
    - *Melosira*[c]
      - *M. arctica* (Ehrenberg) Dickie in Pritchard
    - *Thalassiosira*[c]
      - *T. nordenskioldii* Cleve
  - Pennales[c]
    - *Achnanthes*
      - *A. taeniata* Grunow
    - Amphiprora[c]
      - *A. concilians* Cleve
      - *A. gigantea* var. *septentrionalis* (Grunow in Cleve *et* Grunow) Cleve
      - *A. kjellmanii* Cleve
      - *A. palludosa* Wm. Smith
    - *Amphora*[c]
      - *A. laevis* var. *laevissima* (Gregory) Cleve
      - *A. proteus* Gregory
    - *Cylindrotheca*
      - *C. closterium* (Ehrenberg) Reimann *et* Lewin
    - *Diploneis*
      - *D. litoralis* Cleve
      - *D. litoralis* var. *arctica* Cleve
      - *D. litoralis* var. *clathrata* (Östrup) Cleve
    - *Gomphonema*[c]
      - *G. exiguum* Kützing
    - *Licmophora*[c]
    - *Navicula*[c]
      - *N. algida* Grunow
      - *N. cancellata* Donkin
      - *N. crassirostris* Grunow in Cleve *et* Grunow
      - *N. digitoradiata* (Gregory) Ralfs
      - *N. directa* (Wm. Smith) Ralfs
      - *N. gastrum* (Ehrenberg) Kützing
      - *N. gelida* Grunow
      - *N. membranacea* Cleve
      - *N. novadicipiens* Hustedt
      - *N. pelagica* Cleve
      - *N. ryncocephala* Kützing
      - *N. salinarum* Grunow
      - *N. spicula* (Hickie) Cleve
      - *N. transitans* Cleve
      - *N. transitans* var. *incudiformis* (Grunow in Cleve) Cleve
      - *N. trigonocephala* Cleve
      - *N. valida* Cleve and Grunow
      - *N. valida* var. *minuta* Cleve
    - *Nitzschia*[c]
      - *N. angularis* Wm. Smith
      - *N. brebissonii* var. *borealis* Grunow in Cleve *et* Moller
      - *N. cylindrus* Hasle
      - *N. delicatissima* Cleve
      - *N. dissipata* (Kützing) Grunow
      - *N. distans* Gregory
      - *N. frigida* Grunow
      - *N. grunowii* Hasle
      - *N. hybrida* Grunow in Cleve *et* Grunow
      - *N. laevissima* Grunow in Cleve *et* Moller
      - *N. lecointei* Van Heurck
      - *N. linearis* (Agardh) Wm. Smith
      - *N. longissima* (Brebisson in Kützing) Grunow
      - *N. seriata* Cleve
      - *N. sigma* (Kützing) Wm. Smith
    - *Pinnularia*[c]
      - *P. ambiqua* Cleve
      - *P. quadratarea* (Schmidt) Cleve
      - *P. quadratarea* var. *bicontracta* (Östrup) Heiden in Schmidt *et al.*
      - *P. quadratarea* var. *constricta* (Östrup) Heiden in Schmidt *et al.*
    - *Pleurosigma*[c]
      - *P. angulatum* (Quekett) Wm. Smith
      - *P. elongatum* Wm. Smith
    - *Stenoneis*
      - *S. inconspicua* var. *baculus* (Cleve in Cleve *et* Möller) Cleve
  - Chlorophyceae
    - *Carteria*[c]
  - Chrysophyceae
    - *Dinobryon*
      - *D. balticum* (Schuett) Lemmermann
  - Dinophyceae[c]
    - *Gymnodinium*[c]
    - *Peridinium*[c]
    - *Prorocentrum*[c]
  - Euglenophyceae[c]
    - *Euglena*[c]
  - Craspedophyceae[c]

[a]72 cores 10 cm in diameter, including 2-3 cm of ice and 12-13 cm of water.
[b]Includes both pre- and post-spill sampling periods.
[c]Taxa for which unidentified cells or colonies were found.

like cell densities, was relatively even on a small scale (Table 2). Variation among locations and periods was also relatively low, unlike data on cell densities. Mean chlorophyll *a* concentrations in control enclosures varied from 3.4 to 16.7 mg·m^{-2}; single sample minimum and maximum values were 0.64 and 23.20 mg·m^{-2} respectively. Mean chlorophyll concentrations in control samples increased progressively throughout the study period, from 9.1 ± 3.3 mg·m^{-2} (n = 42) on 18-19 May to 15.7 ± 3.0 mg·m^{-2} (n = 7) on 1-2 June.

Ice Algal Productivity

Ice algal productivity rates reported herein are based on differences between light and dark incubation chambers in the amount of particulate radiocarbon (POC) retained on 0.45 μm cellulose triacetate filters. Dissolved organic radiocarbon (DOC) that passed through the filters was also measured in a total of 87 samples from three of the five sampling periods. The amount of dissolved radiocarbon in the filtrate was up to 4.5 × greater than the amount of particulate radiocarbon retained on the filter, and in only 1 of 87 samples did POC exceed DOC. This was likely because the formalin used to terminate incubations caused cell rupture (see Discussion). Total productivity (POC + DOC) was, therefore, considerably higher than the rates reported in the following section, viz., from 0.2 to 12.7 mg C·m^{-2}·h^{-1}. Even these values likely underestimate total productivity, because a lower vacuum pressure was used in DOC than in POC filtration. Because fewer measurements of DOC were taken (87 vs. 167 samples for POC), the following results concern only particulate carbon productivity. Conclusions should also apply to dissolved organic carbon (and total) productivity, however, because dissolved and particulate carbon productivity rates were strongly correlated ($r = 0.90$; $n = 87$; $P<0.001$).

All incubations were carried out around noon for 2-2.5 h periods. Sky conditions varied during incubation periods and from day to day, and the resultant daily values of surface light during incubations ranged from 13 000 to 20 000 watt-h·m^{-2}. The amount of light reaching the bottom of the ice was much more variable; percent transmission through the ice and snow, measured within each enclosure, varied from 0.11 to 0.77%. This spatial variability was likely the result of variable snow cover. Snow depths, measured at the surface in the estimated locations of the under-ice enclosures, were from 8.5 to 30.6 cm. The estimated amount of light reaching each enclosure during each incubation is given in Table 2. These values varied over an order of magnitude, from 12.2 to 121.7 watt-h·m^{-2}.

Ice algal productivity increased with increasing light over the range of conditions encountered (Fig. 2). There was no evidence of photosynthetic inhibition at the highest light levels (approximately 120 watt-h·m^{-2} in a 2.25 h period). Productivity rates were near zero at the lowest light levels (approximately 20 watt-h·m^{-2}; Fig. 2).

Productivity of ice algae varied considerably among locations (enclosures) and periods: mean productivity rates in controls were from near zero to 2.95 mg C·m^{-2}·h^{-1} (Table 2). The lowest productivity rates were obtained from enclosures with the lowest recorded light values, e.g., the "oil" enclosure at Location 1 and the "BP 1100 WD + oil" enclosure at Location 2 (Table 2). Productivity in control samples increased progressively from 18-19 May (0.85 ± 0.75 mg C·m^{-2}·h^{-1}; n = 31) to 28-29 May (2.48 ± 0.38 mg C·m^{-2}·h^{-1}; n = 5) and decreased slightly by 1-2 June to 2.13 ±0.36 mg C·m^{-2}·h^{-1} (n = 5). Increased productivity was likely related to increased chlorophyll *a* concentrations; however, productivity per unit chlorophyll in control samples also increased progressively from 18-19 May to 28-29 May (0.08 to 0.19 mg C·mg Chl a^{-1}·h^{-1}) and decreased by 1-2 June (0.14 mg C·mg Chl a^{-1}·h^{-1}).

TABLE 2. Under-ice productivity, chlorophyll *a*, microalgal density and *in situ* light data measured in all sampling periods at Cape Hatt, Baffin Island, during 18 May-2 June 1982;[a] productivity, chlorophyll *a* and microalgal density in ice (+ water) samples are assumed to be almost entirely attributable to the ice fraction (see text)

			Treatment					
Variable	Period	Location	Control	Oil[b]	Solidified oil[b]	BP CTD + oil[b]	BP 1100 WD + oil[b]	Corexit 9527 + oil[b]
Productivity ($mg\ C \cdot m^{-2} \cdot h^{-1}$)	Pre-1	1	1.50± 0.18 (3)	0.05 (1)	0.21± 0.05 (3)	2.14± 0.60 (2)	1.08± 0.19 (3)	0.30± 0.04 (3)
		2	1.50± 0.86 (2)	0.82± 0.23 (3)	0.33± 0.09 (2)	0.16± 0.10 (3)	0.11± 0.07 (3)	1.89± 0.34 (3)
	Pre-2	1	1.92± 0.54 (3)	−0.08± 0.05 (3)	0.16± 0.20 (2)	1.82± 0.26 (2)	1.47± 0.24 (3)	0.49± 0.08 (3)
		2	2.95± 1.61 (3)	0.95± 0.52 (3)	0.70± 0.29 (2)	0.88± 0.25 (3)	−0.05± 0.03 (3)	1.38± 0.31 (3)
	Post-1	1	1.78± 0.77 (3)	0.19± 0.03 (3)	1.29± 0.53 (3)	1.16± 0.44 (3)	1.20± 0.29 (3)	1.11± 0.49 (3)
		2	2.11± 0.53 (3)	1.90± 0.38 (3)	1.52± 0.46 (3)	1.28± 0.39 (3)	0.09± 0.07 (3)	0.94± 0.37 (3)
	Post-2	1	2.58± 0.50 (3)	0.30± 0.03 (3)	1.46± 0.48 (3)	2.10± 0.11 (3)	1.57± 0.36 (3)	2.21± 0.15 (3)
		2	2.33± 0.07 (2)	2.18± 0.48 (3)	1.64± 0.55 (3)	1.53± 0.45 (3)	−0.00± 0.04 (3)	1.98± 0.38 (3)
	Post-3	1	2.09± 0.00 (2)	0.38± 0.06 (2)	1.55± 0.48 (3)	1.85± 0.38 (3)	1.38± 0.25 (3)	1.39± 0.16 (3)
		2	2.16± 0.51 (3)	1.79± 0.03 (2)	1.12± 0.24 (3)	1.31± 0.29 (3)	0.07± 0.03 (2)	2.11± 0.42 (3)
Chlorophyll *a* ($mg \cdot m^{-2}$)	Pre-1	1	10.83± 1.65 (4)	3.35± 0.58 (2)	6.04± 0.70 (4)	11.66± 2.74 (3)	10.15± 1.34 (4)	7.65± 2.57 (4)
		2	12.80± 2.41 (3)	11.31± 0.86 (4)	10.85± 4.61 (2)	6.82± 4.14 (4)	5.78± 0.43 (4)	11.66± 1.55 (4)
	Pre-2	1	11.66± 2.72 (3)	6.23± 5.32 (4)	6.95± 2.45 (3)	10.24± 0.28 (2)	10.85± 0.50 (3)	11.44± 5.31 (4)
		2	13.36± 1.94 (4)	10.93± 1.29 (4)	9.73± 2.08 (3)	10.50± 0.61 (3)	3.91± 2.74 (3)	13.98± 2.14 (4)
	Post-1	1	15.64± 1.78 (4)	6.47± 1.20 (4)	14.98± 4.02 (3)	13.76± 1.47 (4)	15.26± 1.41 (4)	12.10± 2.27 (4)
		2	12.04± 2.36 (4)	14.18± 1.55 (4)	14.49± 1.36 (3)	10.77± 0.96 (3)	5.32± 2.50 (4)	12.79± 1.96 (4)
	Post-2	1	14.60± 2.56 (4)	10.93± 2.38 (4)	16.29± 3.30 (4)	11.64± 1.35 (3)	13.47± 3.20 (4)	12.19± 1.68 (4)
		2	13.31± 0.13 (2)	13.67± 2.37 (4)	13.95± 1.63 (4)	9.70± 1.32 (3)	4.25± 1.81 (4)	10.68± 1.46 (4)
	Post-3	1	16.67± 1.92 (3)	10.67± 1.42 (3)	20.18± 2.39 (4)	11.38± 0.39 (3)	13.07± 2.82 (4)	11.81± 4.65 (4)
		2	14.99± 3.76 (4)	13.01± 1.75 (3)	15.10± 4.71 (4)	9.09± 1.78 (3)	5.98± 3.09 (3)	10.72± 2.25 (4)
Microalgae ($cells \cdot m^{-2} \times 10^7$)	Pre-1	1	157.47± 54.39 (4)	9.21± 5.20 (2)	44.31± 20.14 (4)	167.34± 70.13 (3)	100.76± 63.47 (4)	57.80± 31.41 (4)
		2	103.96± 29.16 (3)	105.85± 32.24 (4)	77.00± 37.00 (3)	47.15± 36.17 (4)	21.29± 7.18 (4)	176.55± 68.56 (4)
	Pre-2	1	270.56±130.33 (2)	1.65± 0.68 (2)	20.31 (1)	246.02 (1)	317.91± 97.06 (2)	56.64± 56.41 (2)
		2	332.78± 68.84 (2)	121.69± 12.24 (2)	72.50± 16.42 (2)	126.88 (1)	11.76± 13.75 (2)	240.52± 68.55 (2)
	Post-1	1	249.68±130.96 (4)	15.94± 2.32 (4)	215.87± 83.41 (3)	245.13± 71.14 (4)	205.30± 55.65 (4)	156.49± 42.90 (4)
		2	237.11± 64.51 (4)	268.51± 79.21 (4)	171.21± 26.98 (3)	146.30± 30.31 (3)	21.79± 12.68 (4)	169.18± 34.96 (4)
	Post-2	1	365.27± 9.37 (2)	113.44± 76.33 (2)	261.60± 18.00 (2)	267.40 (1)	228.00± 26.06 (2)	175.96± 59.04 (2)
		2	384.71± 83.81 (2)	255.49± 10.23 (2)	205.19± 2.16 (2)	111.60± 30.82 (2)	20.55± 11.42 (2)	238.18± 56.31 (2)
	Post-3	1	254.37± 15.07 (3)	169.84± 35.17 (3)	359.56± 78.67 (4)	246.17± 47.04 (3)	236.99± 82.82 (4)	229.50± 5.18 (4)
		2	280.22± 13.65 (4)	205.11± 34.07 (3)	322.80±116.94 (4)	167.82± 51.76 (3)	51.34± 41.42 (3)	185.78± 36.85 (4)
Light[c] (Watt-$h \cdot m^{-2}$)	Pre-1	1	—	—	—	—	—	—
		2	—	—	—	—	—	—
	Pre-2	1	86.10	21.50	34.28	75.41	59.26	36.49
		2	117.59	86.10	47.29	73.32	17.31	64.03
	Post-1	1	108.41	24.40	23.01	82.15	56.82	84.13
		2	106.67	79.25	49.39	71.81	14.29	67.63
	Post-2	1	82.85	22.89	36.95	96.45	51.71	62.75
		2	103.30	65.30	57.29	61.01	12.20	77.16
	Post-3	1	80.53	20.45	34.74	72.97	38.81	53.57
		2	121.66	72.39	56.47	61.59	16.97	90.40

[a]Data are expressed as mean ±SD with n in parentheses.
[b]Unweathered Lagomedio crude oil.
[c]Surface radiation multiplied by percent transmission (see text).

Oil Effects

Oil treatments were applied on 23-24 May, and oil concentrations in the water within the enclosures were measured about 5 h after treatment application. Oil concentrations in the water at that time are shown in Table 3. Dispersed oil in concentrations from 5.8 to 36.5 ppm (as measured by ultraviolet fluorescence) was contained within enclosures beneath the ice for approximately 5 h and then released. In contrast, oil concentrations in the water within enclosures containing oil and solidified oil, measured 5 h after treatment, were similar to control values; in these cases, most of the fluorescence was derived from the polypropylene syringes used to collect samples. Oil and solidified oil remained in the enclosures on the under-ice surface during the 12 d post-treatment sampling period; the solidified oil mass remained on the under-ice surface, whereas the pool of untreated oil was overgrown by ice within 2 d of treatment (diver observations). Ice growth was also apparent around the plexiglass enclosures and around polyethylene syringes left on the under-ice surface.

Community Structure: There was no evidence that the group composition of ice microalgae was affected by any oil treatment during the 12 d of post-treatment sampling. During pre-treatment sampling (18, 19 May) in all enclosures and during post-treatment sampling in control enclosures pennate diatoms constituted 87.0-93.7% and microflagellates 5.9-12.7% of total ice algal cells in each enclosure (n = 2-4 samples per enclosure). During post-treatment sampling (26, 27 May and 1, 2 June) in experimental enclosures, the corresponding percentages were 85.0-95.5% for pennate diatoms and 3.7-14.0% for microflagellates.

Density, Biomass and Productivity: Most interactions between

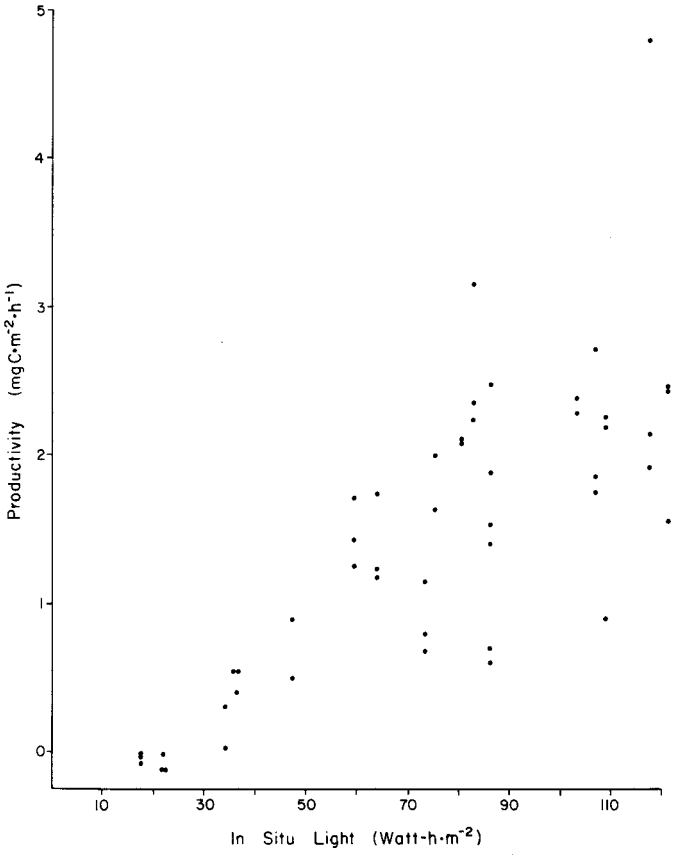

FIG. 2. Ice algal productivity (mg C·m^{-2}·h^{-1}) vs. *in situ* light (watt-h·m^{-2}) at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982. Each point is the productivity rate calculated for one control incubation; one light measurement was made for each set of 2 or 3 productivity rates.

TABLE 3. Oil concentrations (average of two samples) from each under-ice enclosure at Cape Hatt, northern Baffin Island, measured 5 h after treatment application on 23-24 May 1982

Treatment	Oil concentration (ppm)	
	Location 1	Location 2
Control	0.24	0.28
Oil	0.19	0.22
Solidified oil	0.15	0.15
BP CTD + oil	5.80	6.70
BP 1100 WD + oil	15.50	26.50
Corexit 9527 + oil	14.50	36.50

period and treatment factors in two-factor ANOVAs were significant (13 of 16 cases; Table 4). In these cases, the significant interaction terms mean that period-to-period variation was not consistent among treatments, indicating the possibility of an oil effect (Green, 1979). However, other factors besides the treatment could also lead to significant interaction terms.

To determine whether the significant interactions were attributable to the two enclosures with very low levels of light and productivity, these enclosures (treatments) were excluded from the analyses. Results were very similar to those shown in Table 4. Hence, the significance of period-by-treatment interactions (Table 4) was not attributable to effects of low-light conditions.

Because interactions might result from factors other than oil treatments, I examined whether the period-to-period variability

TABLE 4. Results of analysis of variance for standing stocks and productivity of under-ice algae at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982[a]

Variable	Location	Source of Variation			Degrees of freedom[b]
		Period	Treatment	Period by treatment	
Productivity (P)	1	16.46 ***	45.75 ***	3.25 ***	4,5,20/53
	2	7.01 ***	33.68 ***	2.38 **	4,5,20/54
Chlorophyll *a* (B)	1	17.98 ***	11.78 ***	2.56 **	4,5,20/76
	2	2.69 *	33.58 ***	1.47 ns	4,5,20/75
Algal density (D)	1	19.72 ***	17.77 ***	2.39 **	4,5,20/56
	2	19.42 ***	35.90 ***	4.26 ***	4,5,20/58
P/B	1	8.49 ***	34.24 ***	3.19 ***	4,5,20/52
	2	8.43 ***	38.75 ***	3.01 ***	4,5,20/52
P/Light[c]	1	23.60 ***	15.55 ***	5.77 ***	3,5,15/44
	2	8.71 ***	22.34 ***	1.45 ns	3,5,15/44
P/B/Light[c]	1	14.02 ***	9.80 ***	6.07 ***	3,5,15/43
	2	14.15 ***	20.40 ***	3.01 **	3,5,15/43
B/Percent transmission[c]	1	1.13 ns	14.35 ***	2.48 **	3,5,15/61
	2	4.81 **	26.05 ***	1.07 ns	3,5,15/60
D/Percent transmission[c]	1	8.11 ***	13.27 ***	4.11 ***	3,5,15/41
	2	2.65 ns	9.52 ***	2.95 **	3,5,15/42

[a]F-values are shown with significance levels (ns = P>0.05; * P≤0.05; ** P≤0.01; *** P≤0.001).
[b]Degrees of freedom shown are numerator df for period, treatment and period-by-treatment interaction, followed by denominator df.
[c]All analyses including light or percent transmission exclude data from Period 1, where percent transmission data were not recorded.

among treatments was consistent with expected oil effects. Expected oil effects would include (1) marked deleterious effects of oil relative to controls, (2) immediate effects in dispersed oil treatments, followed by recovery, (3) delayed effects in oil or solidified oil treatments and (4) effects in dispersed oil treatments that were consistent with measured oil levels — i.e., least in BP CTD; more pronounced in Location 2 than Location 1 for Corexit 9527 and BP 1100 WD. Inspection of the data (Fig. 3) showed little evidence for any of these expected oil effects.

There were no marked deleterious effects of any oil treatment on any of the variables. As previously mentioned, these results apply to areas where untreated or chemically dispersed oil contacted the ice and then moved away or areas near untreated or solidified oil that remained in contact with the under-ice surface. Decreases in some or all variables from the immediate pre-spill to immediate post-spill periods were evident in some enclosures (e.g., Corexit + oil, Location 2), but these were also evident in the control. There were no marked immediate effects of dispersed oil treatments, nor was there any evidence of recovery in later post-spill periods. Differences among dispersants or between locations were not consistent with differences in measured oil concentrations.

Inspection of the data for oil and solidified oil treatments indicated the possibility of a stimulatory effect of these treatments on the biomass and productivity of under-ice algae. Overall, productivity and standing stocks in control samples increased during the study period. Progressive (period-to-period) increases in biological variables, however, were not common in any enclosure except the solidified oil and, to a lesser extent, untreated oil enclosures. This progressive increase was not

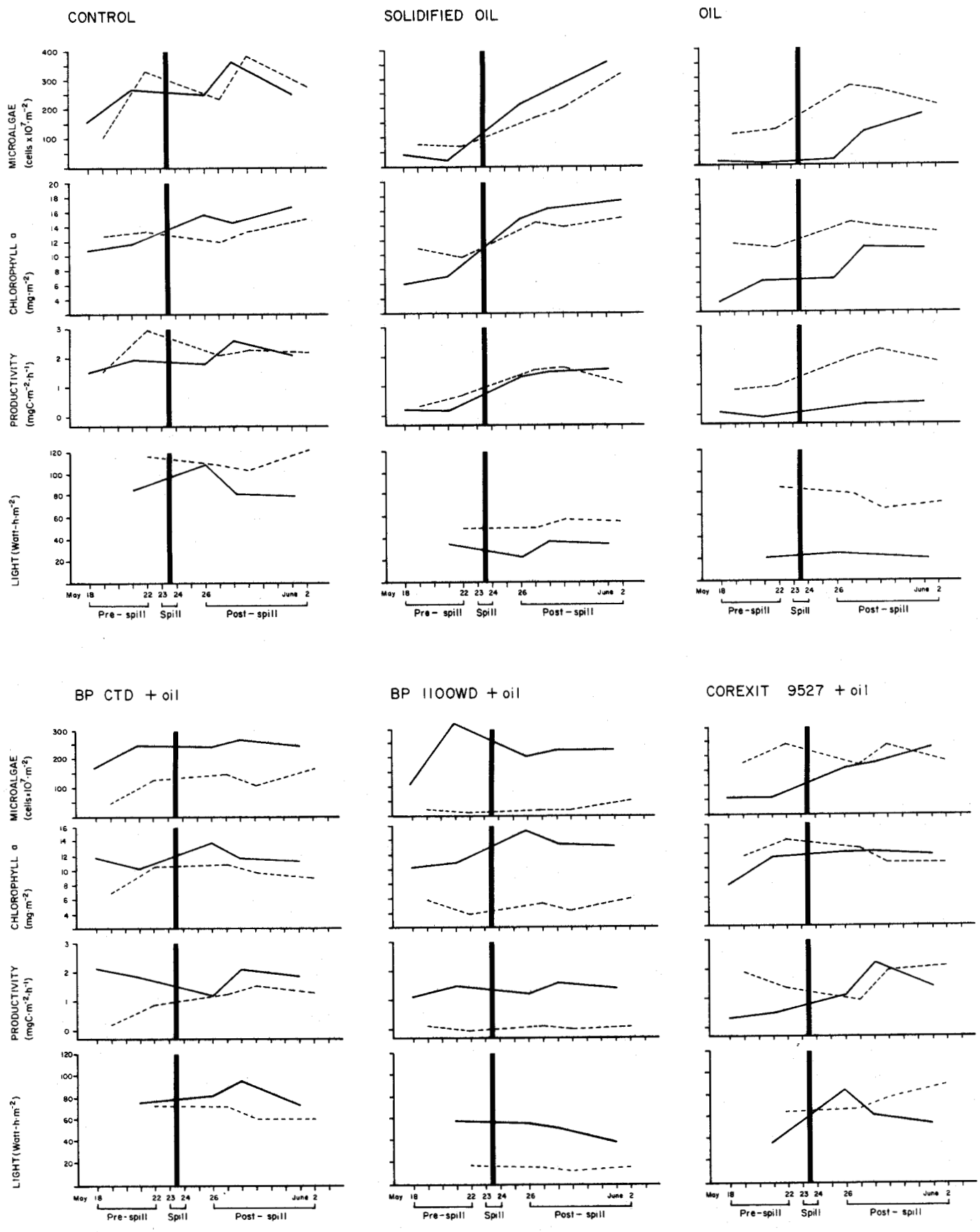

FIG. 3. Under-ice productivity, chlorophyll *a*, microalgal density and *in situ* light data in two locations (1 = solid lines; 2 = dashed lines) at Cape Hatt, northern Baffin Island, during 18 May-2 June 1982.

clearly related to increases in light, particularly in the case of the solidified oil treatment. In some other enclosures, increases in biomass or productivity occurred between the pre-spill sampling periods, but rarely were those increases sustained throughout the post-spill sampling period. Differences among enclosures (treatments) in the nature of the increases also may have been related to snow conditions and, in particular, changes in snow depth that occurred immediately before the study period.

DISCUSSION

The ice algal bloom at Cape Hatt in May 1982 was typical of those reported elsewhere under arctic landfast ice, including that at Cape Hatt in May 1981 (Cross, 1982b). Similarities between this and previous studies are evident in data for density, biomass and productivity, both in near-ice water (*cf.* Alexander *et al.*, 1974; Cross, 1982a,b; Grainger and Hsiao, 1982) and in the bottom layer of ice (*cf.* Apollonio, 1965; Clasby *et al.*, 1973; Dunbar and Acreman, 1980; Hsiao, 1980; Cross, 1982a,b). Differences among locations or years are few: considerably higher ice algal biomasses have been reported previously, likely because of differences in snow cover (Alexander *et al.*, 1974; Cross, 1982a), and the timing of the spring bloom can be variable. The bloom apparently began to decline earlier at Barrow, Alaska, in 1972 (Clasby *et al.*, 1973) and possibly at Cape Hatt in 1982 (present study) than at Cape Hatt in 1981 (Cross, 1982b). Overall, the similarities in ice algal abundance and productivity among locations and years indicate that results of the present study concerning oil effects on ice algae under landfast ice can be applied to most other arctic locations.

The high concentrations of dissolved organic radiocarbon (DOC) measured in the present study (up to 4.5 × particulate organic carbon) were unexpected. On average, DOC accounted for 71% of total (dissolved + particulate) production. This percentage is near the upper end of the range of values previously reported in coastal and oceanic waters (see Sharp, 1977, for a review; Smith *et al.*, 1977; Lancelot, 1979; Larsson and Hagström, 1979, 1982; Mague *et al.*, 1980; Sellner, 1981; Wolter, 1982; Jensen, 1983). Possible sources of the dissolved organic carbon include active release of photosynthetic products by healthy algae (e.g., Fogg, 1977) and lysis of plant cells through various means (see Cole *et al.*, 1982). In the present study, cell rupture during filtration was avoided by the use of small (20 ml) sample volumes and low (<120 mm Hg) vacuum pressures (see Mague *et al.*, 1980), but cells may have leaked contents into the medium when formaldehyde was added to the incubation chambers (see Silver and Davoll, 1978).

Regardless of the mechanism of DOC release, however, dissolved organic radiocarbon present in the medium was originally fixed by algae and must be included in our estimates of productivity. Thus mean ice algal productivity (particulate + dissolved) was 4.40 ± 3.68 mg $C \cdot m^{-2} \cdot h^{-1}$ (n = 41 control samples) over the range of light levels studied at Cape Hatt in May 1982. The highest productivity rate measured (single sample) was 12.7 mg $C \cdot m^{-2} \cdot h^{-1}$. Even higher productivity rates would be expected in areas where, unlike the present study area, ice algal biomass was very high (e.g., Pond Inlet in 1979; Cross, 1982a).

No adverse effects of oil on under-ice algal density, biomass or productivity were detected for the specific oil spill scenarios addressed by the present study. These results are in conflict with the rather large body of literature on effects of oil on other types of microalgae. Cell death or inhibition of growth or photosynthesis has been reported for unialgal cultures grown in the laboratory (Dunstan *et al.*, 1975; Hsiao, 1978; Mahoney and Haskin, 1980; Karydis, 1982; Østgaard *et al.*, 1984; Van Baalen and O'Donnell, 1984; Hegseth and Østgaard, 1985), for natural phytoplankton communities (Gordon and Prouse, 1973; Shiels *et al.*, 1973; Hsiao *et al.*, 1978; Trudel, 1978) and for planktonic or benthic microalgae in controlled ecosystem experiments (Skjoldal *et al.*, 1982; Throndsen, 1982; Dahl *et al.*, 1983; Parsons *et al.*, 1984; Farke *et al.*, 1985a,b). Many of these studies have found differential sensitivity among species, leading some authors to suggest that in natural communities such differences would lead to effects on community structure, succession and trophic relationships (Shiels *et al.*, 1973; Dunstan *et al.*, 1975; Hsiao, 1978; Hsiao *et al.*, 1978). In recent field experiments, such changes have been observed (Parsons *et al.*, 1976; Lee and Takahashi, 1977; Throndsen, 1982; Vargo *et al.*, 1982; Parsons *et al.*, 1984). No such effect on ice algal community structure (i.e., dominant species or ratios of diatoms to flagellates) was observed in the present study.

The lack of adverse effects of dispersed oil on ice algae at Cape Hatt may be related to the 2 d recovery period between exposure and the first post-exposure sampling. Relatively high concentrations of dispersed oil (up to 37 ppm) contacted the ice for only 5 h. Most previous reports of adverse effects of oil on microalgae are based on longer exposure periods, ranging from days in laboratory or *in situ* incubations to weeks or months in controlled ecosystem experiments. A few previous studies have indicated that short (2-8 h) exposures to oil can inhibit microalgal photosynthesis at concentrations as low as 0.1 ppm (Trudel, 1978), although threshold concentrations were more often 1-100 ppm (Hsiao *et al.*, 1978; Vandermeulen *et al.*, 1979; Kusk, 1981; Karydis, 1982). In all of those experiments, however, productivity was measured immediately following exposure, whereas a 2 d recovery period preceded the first measurements in this study. In previous studies, inhibitory effects of oil on microalgae have been transitory (Mahoney and Haskin, 1980), with recovery periods on the order of days. Recovery was evident less than 2 d following 1-3 d exposures of diatoms to 7 or 14 ppm Ekofisk crude oil (Østgaard *et al.*, 1984), and following 6 d of repeated exposure (twice daily) of intertidal microalgae to 2-4 ppm chemically or mechanically dispersed crude oil (Farke *et al.*, 1985a). It is not known if any adverse effects on ice algae occurred at Cape Hatt during the 2 d following exposure to oil.

The only possible effect of oil detected in this study was stimulation of ice algal growth and productivity in enclosures treated with solidified oil and untreated oil. Very low oil concentrations may have been present in the water within these enclosures during the post-treatment period; oil concentrations in this water immediately after treatment application were similar to those in control enclosures, but no measurements of oil concentrations were made after that time. Stimulation of growth or photosynthesis in microalgae exposed to low (ppb) concentrations of oil has been a common result in many previous studies. Where stimulation has been observed in unialgal cultures (Dunstan *et al.*, 1975; Prouse *et al.*, 1976; Hsiao, 1978; Nunes and Benville, 1979; Mahoney and Haskin, 1980; Karydis, 1982), it can be concluded that stimulation was a direct effect. During *in situ* experiments and accidental oil spills, on the other hand, apparent growth stimulation may have been an indirect result of reduced grazing (Lännergren, 1978; Bakke and Johnsen, 1979; Elmgren *et al.*, 1980; Johansson, 1980; Vargo *et al.*, 1982). At Cape Hatt, densities of meiofaunal copepods, poly-

chaetes and nematodes were not affected in either the untreated oil or solidified oil enclosures (Cross and Martin, 1987), but grazing rates may have been reduced.

Thus, the disproportionate increases in ice algal growth and productivity in untreated and solidified oil enclosures may have been a result of direct stimulation or reduced grazing pressure caused by low oil concentrations. This possibility is supported by the greater apparent stimulation in solidified oil than in untreated oil enclosures, because the solidified oil did not become overgrown by ice as did the untreated oil. However, it is also possible that temporal changes in other factors affecting ice algae were not consistent among the various treatment enclosures. The most likely such factor was snow depth, which is inversely related to ice algal biomass (Alexander *et al.*, 1974; Cross, 1982a). Snow depth varied both spatially and temporally during the study period because of wind drift.

The results of this study must be considered in relation to the experimental design of the study. Firstly, we created two specific scenarios for the impingement of oil onto the under-ice surface: low concentrations of dispersed oil contacting the ice for a short period of time, and untreated oil and solidified oil remaining in place on the under-ice surface. Secondly, in enclosures containing untreated and solidified oil, sampling was not carried out directly in the oiled areas. Therefore, two of the three types of effect identified by Hsiao (1978) for an oil spill under the ice, viz., physical damage by direct coating with oil and decreased productivity because of shading, would not have been detected in the present study. Thirdly, because the first post-exposure sampling was 2 d after exposure, immediate and transitory effects would not have been detected for any of the oil treatments. However, the apparent complete recovery within 2 d indicates that no long-term effects would occur after exposure to a short pulse of concentrated dispersed oil.

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