



Springtime sensible heat, nutrients and phytoplankton in the Northwater Polynya, Canadian Arctic

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(Received 1 June 1995; accepted 8 January 1996)

Abstract—Sampling was conducted in the Northwater Polynya (between 70°20' and 77°20'N), on 17 and 19 May 1991. At each of the 14 sampling stations, CTD profiles were recorded from surface to bottom and nutrients and phytoplankton were determined at four depths down to 30 m. The presence, between 220 and 400 m, of water temperatures >0°C is an indication that, in winter, the West Greenland Current enters the Northwater along the Greenland coast. The warm water is progressively mixed as it moves northward and eastward. It was thus hypothesized that sensible heat is as an important factor in keeping the Northwater open. Measured chemical and biological variables were quite homogeneous on the vertical down to 30 m and they showed longitudinal gradients. From east to west, the average concentrations of nutrients increased (phosphate from 0.5 to 1.4, nitrate from 3.7 to 10.8, and silicate from 6.8 to 34.2 mmol m⁻³), whereas the areal concentrations of phytoplankton decreased (from 47 to 9 × 10⁹ cells m⁻² and from 506 to 50 mg Chl a m⁻²). Nutrient ratios indicated possible silicon deficiency in the easternmost part of the polynya. Diatoms dominated cell numbers (≥87% at all stations). Concentrations of the three nutrients were inversely correlated with both Chl a and cell numbers. The Y-intercepts of regressions of Chl a on nutrients provided an estimate of potential maximum biomass in the upper 30 m, which was ca. 600 mg Chl a m⁻², or lower if there was silicon limitation. The overall picture was that of a diatom bloom, moving westward and progressively exhausting the nutrients. Initiation of the bloom appeared to have been linked to the absence of sea ice. A source of heat for this would have been the above sensible-heat process. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

Polynyas are broad, irregularly shaped areas of open (or very lightly ice-covered) water surrounded by sea ice. Recurrent polynyas are found year after year at fixed geographical

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locations, which indicates that they are driven by recurring physical processes. The two basic mechanisms responsible for polynya formation are associated with latent-heat and sensible-heat processes (Smith *et al.*, 1990). In a pure latent-heat polynya, ice is continuously formed and advected away by strong winds and currents, the heat loss to the atmosphere being balanced by the latent heat of fusion of the ice. In a sensible-heat polynya, the heat loss is supplied by the cooling of a continuous flux of warm water rising to the surface. Such a flux may be caused by either vertical convection due to salt released into the water by sea ice growth or upwelling driven by wind and/or water currents and changes in bottom topography. Polynyas result from a combination of all these factors in differing proportions. Based on observations that marine mammals (e.g. Stirling *et al.*, 1981) and birds (e.g. Brown and Nettleship, 1981) are abundant in the open waters of polynyas, it has been hypothesized that their plankton productivity is high (e.g. Dunbar, 1981).

The Northwater is one of the largest polynyas in the Northern Hemisphere. It occupies Smith Sound and the northern part of Baffin Bay, between Greenland and Ellesmere Island. Fig. 1 show these features and average positions of the fast ice edge from January through June. In summer, there is no fast ice in Smith Sound and Lady Ann Strait (between Devon and Ellesmere Islands). Available information led Muench (1971) to the conclusion that mechanical ice removal (resulting from current and winds) was probably the most important factor in keeping the Northwater open. The ice bridge, commonly observed to span northern Smith Sound in winter, prevents ice from the north from entering the region. In that scheme, significant upward transport of heat in winter, by vertical convection or offshore upwelling, is unlikely. The Northwater was thus generally considered to be a latent-heat polynya.

Studies jointly conducted in the Northwater by McGill University and ETH Zurich, between 1972 and 1981, included meteorological observations at three ground stations and remote sensing data from both aircraft and satellite. Important findings were that, although the ice does not consolidate in the Northwater in winter, the area is often 95% ice covered and that, in January, >50% of this ice is <30 cm thick and moves at an average speed of 17 km d^{-1} . An average heat loss, during winter, of *ca.* 180 W m^{-2} was attributed to this thin ice and the open waters (Steffen, 1986; Steffen and Lewis, 1988). A very interesting result of overflights with a radiation thermometer was the discovery of "warm water cells" in the Northwater during winter, i.e. patches of open water of dimension *ca.* 1 km with temperatures above the freezing point, which were concentrated along the Greenland coast (Steffen, 1985). The author concluded that these were indicative of upwelling, probably caused by persistent northerly wind with a mean value of 7.5 m s^{-1} during winter. It was hypothesized (Steffen, 1985; Steffen and Ohmura, 1985) that this upwelling might be an important mechanism for the formation and maintenance of the polynya.

In a study on the formation of Baffin Bay bottom and deep waters; Bourke and Paquette (1991) estimated total ice production in the Northwater in a year. They investigated the possibility that sensible heat could contribute to the heat loss to the atmosphere, which would reduce ice growth, and they came to the conclusion that errors in Steffen's (1985) observations were such that, for the most part, he only observed freezing point water at surface. In their discussion, they note that the deepest water available for upwelling would be from *ca.* 300 m and that the highest temperature found between that depth and the surface in the Smith Sound area was -0.6°C (September 1986; data from the CCGS *Sir*

John Franklin cruise). They concluded that upwelling of "warm" water was not a major factor in the heat balance of the Northwater.

Mysak and Huang (1992) coupled a latent-heat polynya model to a reduced-gravity, coastal upwelling model to simulate the formation and maintenance of the Northwater Polynya. In their model, northerly winds (latent-heat mechanism) were responsible for changes occurring on the order of days, whereas upwelling of warm subsurface water (i.e. sensible heat) along the Greenland coast was responsible for the gradual southward extension of the ice edge in this region, which occurred on a time-scale of the order of weeks. In a following modelling exercise, Darby *et al.* (1994) found that, with the exception of late spring, the southern ice edge of the polynya could be simulated in terms

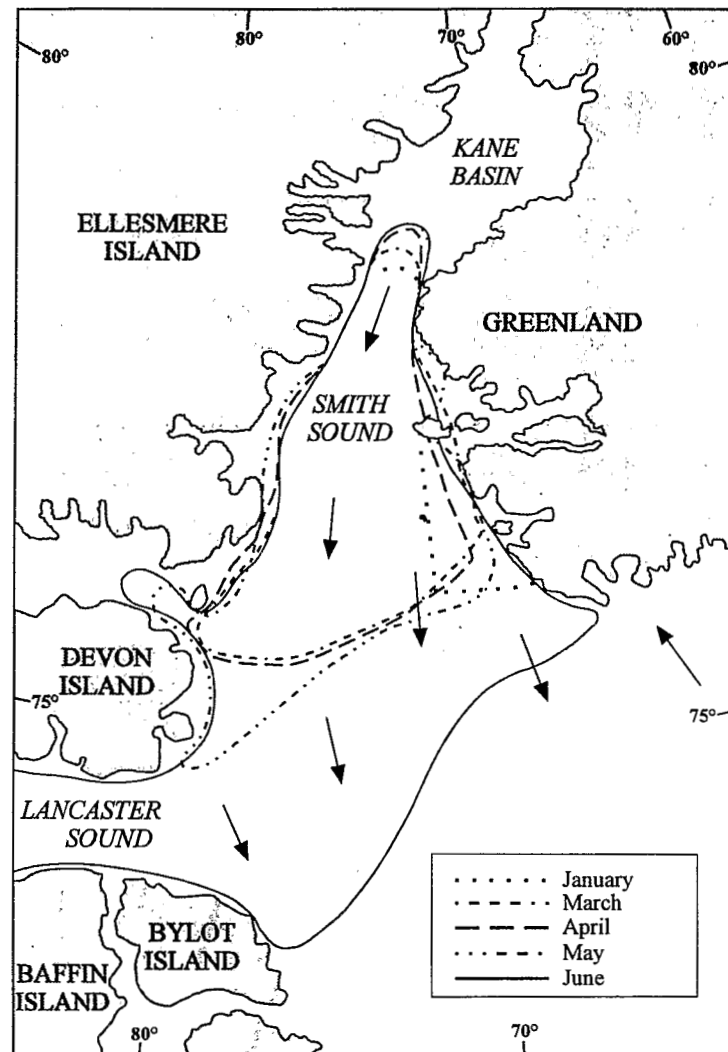


Fig. 1. Ice cover in the Northwater Polynya. Approximate monthly averages, with arrows indicating the mean directions of prevailing winter winds (from Dunbar, 1969, and Muench, 1971).

of latent heat alone. In late spring, when the heat loss to the atmosphere is reduced, their model shows that the postulated sensible heat flux (upwelling) could play an important role in determining the position and shape of an ice edge, especially near the West Greenland coast.

There are few direct measurements of primary and secondary biological production in polynyas during late winter and spring, because of obvious logistical difficulties. Preliminary observations in the Northeast Water Polynya (northeast of Greenland; Hirche *et al.*, 1991), at the end of June 1984, are consistent with the hypothesis of enhanced plankton production within the polynya. At the very beginning of summer, diatoms in the Northeast Water were blooming (Chl a concentrations between *ca.* 60 and >90 mg m $^{-2}$) and production of eggs by the copepod *Calanus glacialis* was high. In contrast, under the surrounding pack ice, the biomass of phytoplankton was low (<20 mg Chl a m $^{-2}$) and production of eggs almost nil. In the marginal ice zone, east of the polynya, Chl a concentrations were <60 mg m $^{-2}$ and production of eggs was very low. No such information exists, so far, for the Northwater Polynya. However, the area is known to be of significance to more species of marine mammals than any other polynya in the Canadian Arctic (Stirling *et al.*, 1981). The Northwater and associated polynyas in Jones and Lancaster Sound are feeding areas for marine mammals and a substantial population of polar bears. This has been taken as evidence that the area is highly biologically productive.

In spring 1991, it was possible to charter the Canarctic ore carrier MV *Arctic* for 48 h, during her first trip to the Canadian Arctic that year. During this short cruise, the first set of springtime physical and biological oceanographic data ever collected in the Northwater Polynya was acquired. The study was undertaken with the aims of (1) revisiting the physical mechanisms that keep this polynya open, i.e. latent versus sensible heat, on the basis of springtime observations; and (2) assessing the significance of physics for biological production.

2. MATERIALS AND METHODS

Sampling was conducted in the Northwater Polynya on 17 and 18 May 1991. There were 14 stations, occupied between 76°20' and 77°20'N along three transects. One transect was oriented south to north, i.e. parallel to the west coast of Greenland, and two transects were roughly east to west (Fig. 2). Characteristics of the sampling stations are summarized in Table 1.

At each station, temperature/salinity profiles were recorded using Guidline CTD equipment, with a water bottle on the cast for salinity calibration. Water samples for biological measurements were collected with a 4-l Niskin bottle at 2.5, 7.5, 15 and 30 m. Subsamples were immediately filtered on pre-combusted (at 400°C for 24 h) Whatman GF/F glass fibre filters (50-ml syringes equipped with 25-mm Sweenex filter holders) and frozen in cryovials at -18°C for later determination of dissolved inorganic nutrients. In addition, 200-ml subsamples were filtered on 25 mm GF/F filters (nominal pore size: 0.7 μ m) for later determination of chlorophyll *a* (Chl a), and 200-ml to 400-ml subsamples were filtered on pre-combusted 25-mm GF/F filters for later determination of particulate organic carbon (POC) and nitrogen (PON). All filters were kept frozen. Additional 250-ml subsamples were preserved with acidic Lugol's solution and formaldehyde for phytoplankton counts.

Laboratory analyses were performed after the cruise. Concentrations of phosphate,

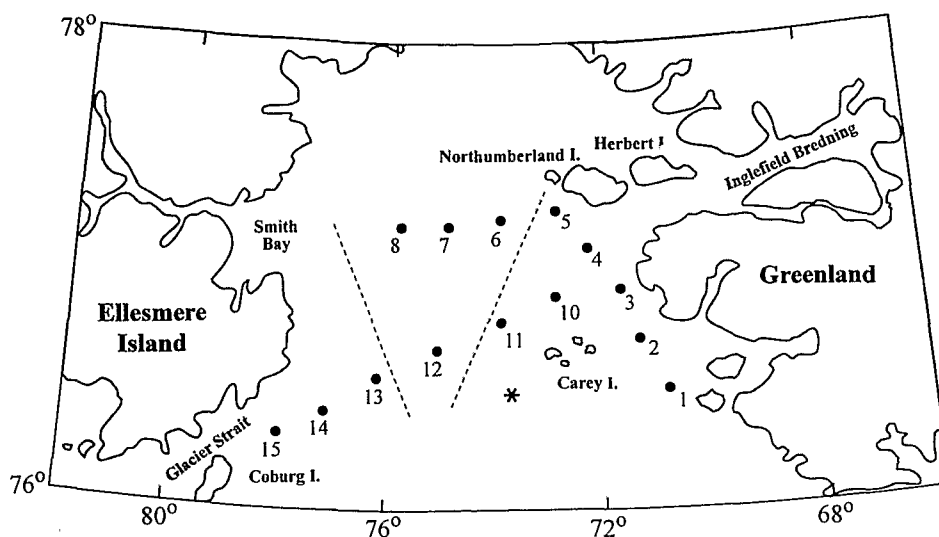


Fig. 2. Sampling area in the Northwater Polynya, showing locations of the Carey Islands and the 14 stations along three transects (station 9, initially planned to extend the second transect west of 77°W, was not sampled because of heavy ice). The star shows the location of a current meter mooring over the winter 1985–86 (Ross, 1991). Dashed lines: boundaries between the three clusters of stations, as determined from the abundances of phytoplankton taxa (Table 3).

Table 1. Location and depth of the 14 sampling stations (date and time of sampling and temperature above freezing (°C) at surface, i.e. difference between measured surface temperature (T) and freezing point calculated from measured surface salinity (T_f); stations 5 and 15 were sampled twice)

Station	Latitude (north)	Longitude (west)	Depth (m)	Date (May 1991)	Time (GMT)	$T - T_f$ ($\pm 0.002^\circ\text{C}$)
1	76°23.0	71°29.1	572	17	02h 20	0.228
2	76°43.4	71°43.4	510	17	04h 45	0.147
3	76°50.0	72°05.5	761	17	06h 34	0.254
4	77°03.5	72°25.7	530	17	08h 28	0.305
5	77°18.0	72°48.9	331	17	10h 28	0.266
5	77°18.0	72°48.9	331	17	11h 31	0.260
6	77°19.6	73°54.4	486	17	13h 04	0.150
7	77°18.0	74°49.8	658	17	14h 48	0.024
8	77°18.2	75°56.3	558	17	16h 40	0.039
9	Not sampled because of heavy ice					
10	76°50.3	73°17.0	163	17	20h 58	0.150
11	76°44.3	74°13.1	521	17	23h 41	0.125
12	76°39.3	75°01.8	439	18	01h 04	0.114
13	76°32.9	76°12.3	100	18	03h 13	0.094
14	76°26.6	77°02.9	254	18	14h 58	0.029
15	76°20.2	77°51.9	236	18	06h 38	0.065
15	76°20.2	77°51.9	236	18	07h 23	0.057

nitrate and silicate were determined using an Alpkem autoanalyzer (Parsons *et al.*, 1984). Concentrations of Chl *a* were measured fluorometrically (Parsons *et al.*, 1984), after overnight extraction of ground filters in 90% acetone at 4°C followed by centrifugation. Concentrations of POC and PON were determined on a mass spectrometer (Tracermass, Europa Scientific, Crewe, U.K.). Phytoplankton cells were identified and enumerated under the inverted microscope (Lund *et al.*, 1958).

3. RESULTS

3.1. Temperature and salinity

Figure 3 shows the actual extent of the Northwater Polynya, on the day before sampling started. The main features of the polynya in 1991 correspond quite well to average observations in previous years (Fig. 1), except that the ice on the western side of the polynya was heavier than usual.

Table 1 gives the difference between surface temperature and freezing point at the surface (calculated from salinity). The horizontal distribution of isopleths drawn from these differences shows a clear westward decrease (Fig. 4). Temperature profiles at stations 1, 3, 7 and 12 are shown in Fig. 5. The surface mixed layer often extended down to only *ca.* 30 m (Fig. 5a,b). Beneath that depth, the situation was variable. All profiles show a great deal of interleaving structure, well traced by temperature, which had little effect on density at these near freezing values. This is indicative of strong advective water movement, which is corroborated by the fact that the pressure record from station 1 shows that the CTD fish moved more or less horizontally at times when the cable was being let out. Previous experiences of this type indicate horizontal velocities of the order of 1 m s^{-1} and, in any case, the profiles clearly show that the water was highly turbulent and mixing. In the 220-m to 400-m depth interval, the water at station 1 was above 0°C and up to 2.4°C above freezing (Fig. 5a). As illustrated by the profiles for stations 3, 7 and 12 (Fig. 5b-d), maximum temperature along the profiles progressively decreased to the north and west of station 1, as also did the thickness of the "warm" layer.

Because of the strong horizontal shear, time constant correction cannot be properly made to relate conductivity sensor output to that of the thermometer, with the result that the accuracy of point salinity measurements is low. However, smoothed salinity profiles can be produced, where the detail is sacrificed to allow acceptable error bars (± 0.01 psu). Figure 6 shows such a smoothed salinity profile for station 1, from which it can be concluded that, in spite of the large temperature spikes, there were no density inversions. The overall impression from the 14 profiles is a very dynamic situation, with major changes in physical properties occurring over time scales of 1 h or less, down to at least 200 m.

3.2. Nutrients and phytoplankton

Two-way analyses of variance (stations \times depths) were performed on each measured chemical and biological variable. Differences among stations were highly significant in all cases ($p < 0.01$) but there were no significant differences among sampling depths for any variable ($p > 0.05$). Coefficients of variation (standard deviation/mean), computed on data from the 14 stations separately, ranged between *ca.* 5 and 30% for each variable, and examination of vertical profiles did not evidence any systematic structure on the vertical for any variable. Consequently, all data were linearly integrated between 2.5 and 30 m. In

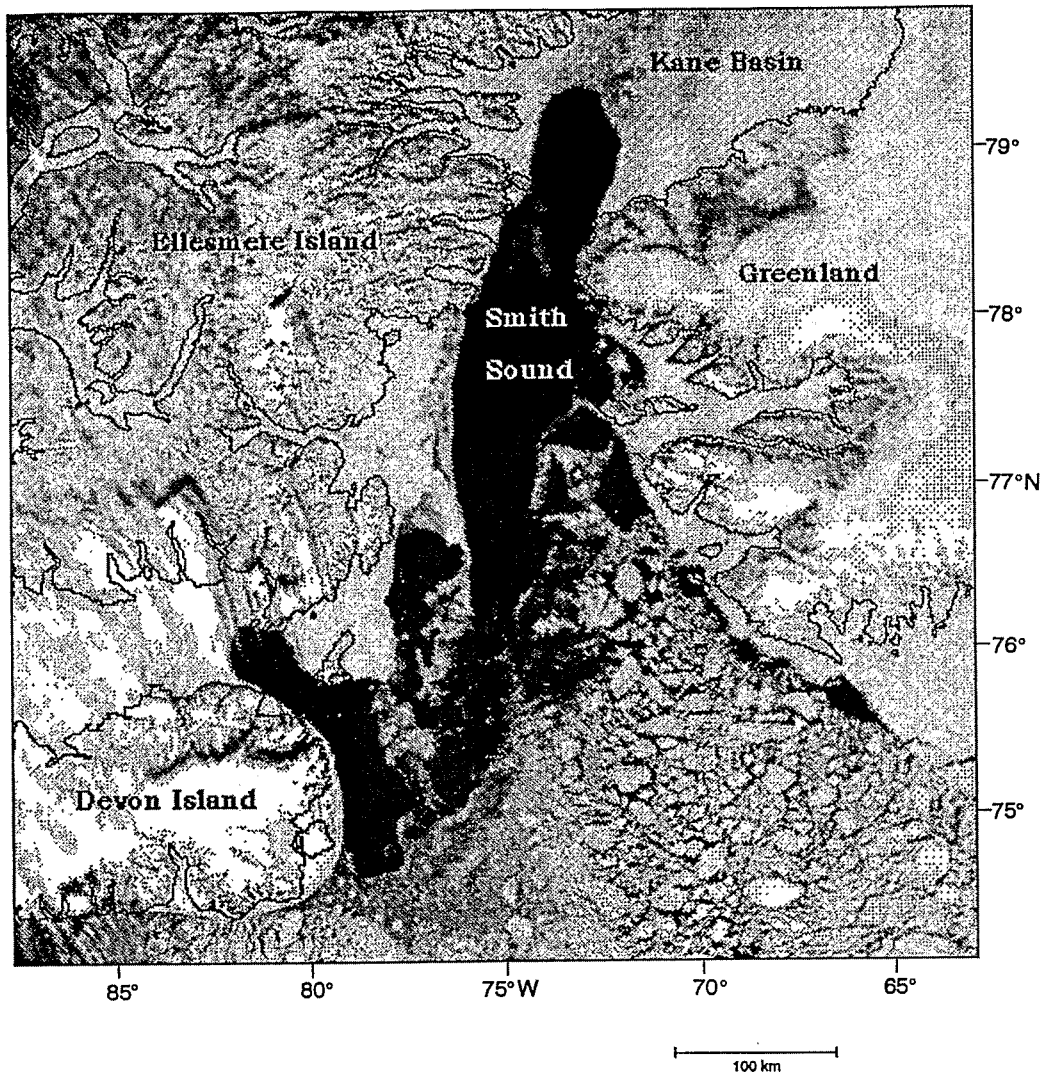


Fig. 3. Image of the Northwater area formed by the AVHRR scanner on the NOAA 11 weather satellite from an altitude of 850 km on 16 May 1991, i.e. the day before our observations commenced. This is not a true map projection, but the simplest standard computer display. Latitude intervals (in degrees) are the same at the top and bottom of the image and longitude intervals the same at the east and west edges. Thus, the scales are equal at the centre of the image but features spread in longitude to the north and shrink to the south. Image processed at the Institute of Ocean Sciences, Sidney, BC, Canada.

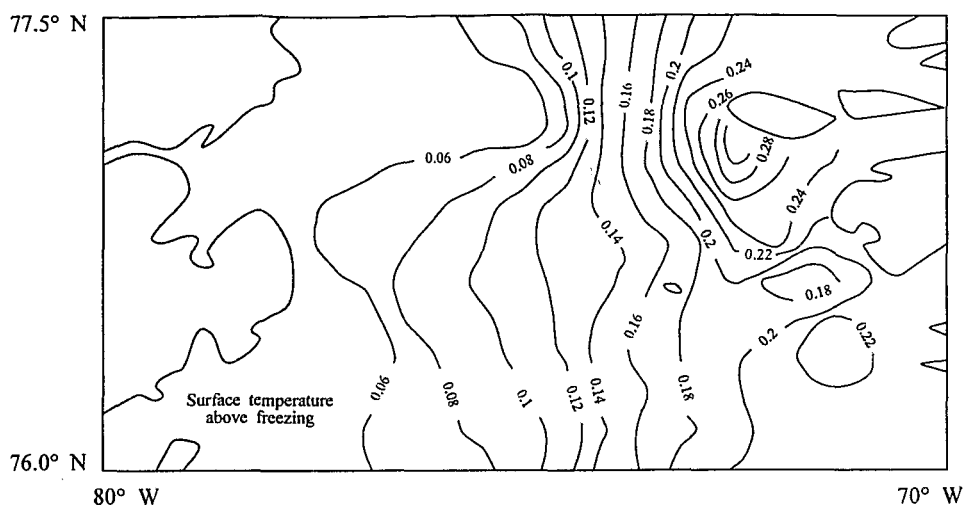


Fig. 4. Temperature above freezing ($^{\circ}\text{C}$) at surface (see Table 1).

the remainder of the paper, except when otherwise specified, values will be given as either average concentrations per unit volume (i.e. depth integrated values divided by 27.5 m) or areal concentrations down to 30 m (i.e. depth integrated values multiplied by 30/27.5).

The horizontal distributions of nutrients (Fig. 7) and phytoplankton (Chl *a* and cell numbers; Fig. 8) exhibited longitudinal gradients. From east to west (Table 2), the average concentrations of nutrients increased and the concentrations of phytoplankton decreased. Similarly, the POC:PON and POC:Chl *a* ratios at individual depths generally increased westwards.

Concentrations of cells belonging to the various taxa were used to determine groups of stations, by subjecting the matrix of similarities between pairs of stations (Steinhaus coefficient) to both single and complete linkage clustering (Legendre and Legendre, 1983). The two methods produced the same three, spatially coherent clusters of stations (Fig. 2). The average concentrations for the various taxa in each cluster are given in Table 3. The easternmost group of stations (1–4 and 10–11) was characterized by lower proportions of centric diatoms and higher proportions of pennate diatoms than in the two other groups. The westernmost group of stations (13–15) was characterized by higher proportions of dinoflagellates. Overall, cell numbers were largely dominated by diatoms ($\geq 87\%$ at all stations).

As expected from the parallel horizontal distributions of Chl *a* and cell numbers (Fig. 7), there was a good correlation ($r^2 = 0.60$, $n = 56$, $p < 0.001$) between the two variables. Concentrations of the three nutrients were inversely related to both Chl *a* (Fig. 9) and cell numbers (not shown). In the case of silicate, removing stations 1 and 2 drastically increased the correlation with Chl *a* (r^2 went up from 0.43 to 0.75).

4. DISCUSSION

4.1. Sensible heat

Water temperatures observed between 250 and 350 m, at station 1 in May, are warmer by ca. 1.4°C than the highest value (-0.6°C) reported by Bourke and Paquette (1991) at

300 m in September. This discovery of deep "warm" water in spring (Fig. 5a,b) leads to the hypothesis that the West Greenland Current moves north in winter and enters the Northwater through the channel between the Carey Islands and the Greenland coast. This is indeed the only possible source for the observed warm water. Such a seasonal northward movement could be attributed to the difference between summer and winter weather patterns in Baffin Bay and Davis Strait. The charts of mean sea level isobars given by Maxwell (1980) show that, in January, the winds must be about five times as strong as those typically experienced in August. These winds blow north along the West Greenland coast and the low pressure centres also move from south to north. These data also show that the major winter cyclonic storms are 50% more common in this area than the comparatively weak summer cyclones. Station 1 would then be representative of the input condition to the Northwater. The fact that maximum temperature along the profiles and the thickness of the warm layer progressively decrease to the north and west of station 1 indicates progressive northward and westward mixing (Fig. 5). A flow of warm water north and west from station 1 is consistent with the observed westward decrease, at surface, of the temperature above freezing (Fig. 4). It follows that sensible heat cannot be ignored as an important factor that keeps the Northwater Polynya open.

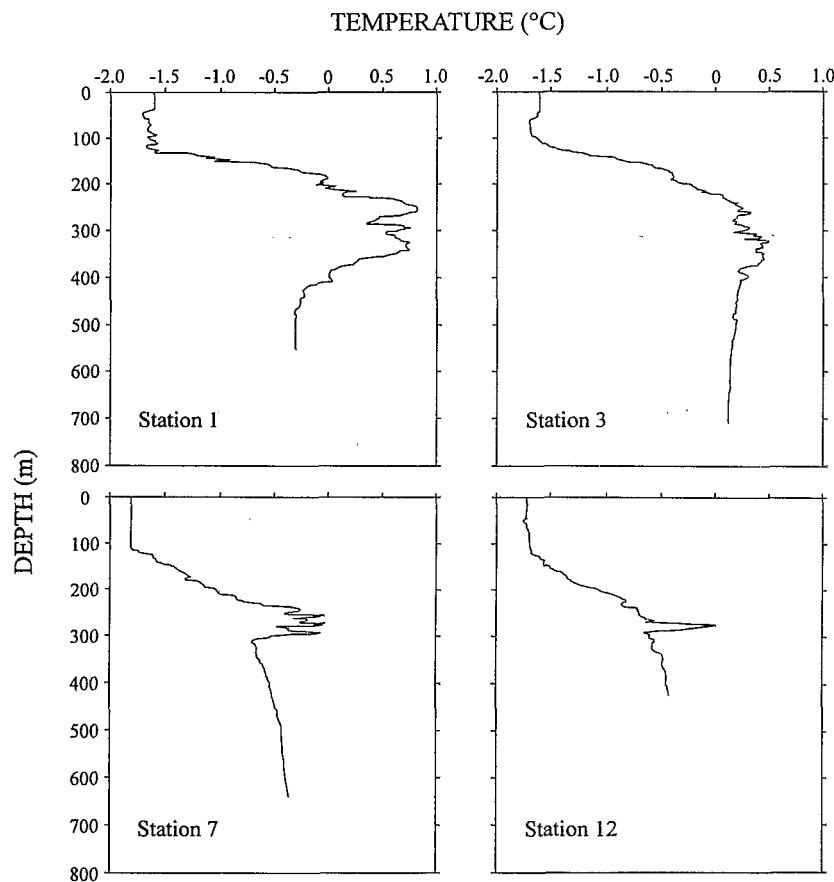


Fig. 5. Vertical temperature profiles at stations 1, 3, 7 and 12.

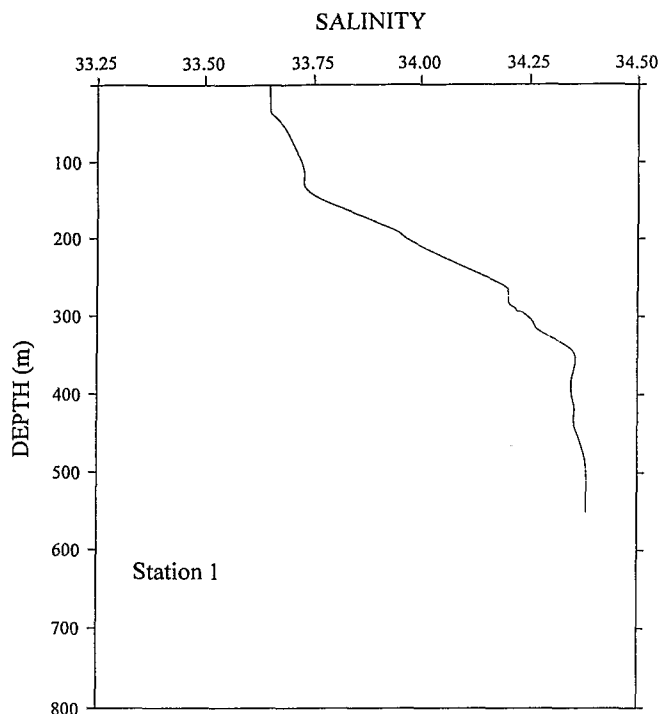


Fig. 6. Smoothed salinity profile at station 1.

Current meters were moored in the area over the winter of 1985–86 (Ross, 1991). One of these moorings was located near the present sampling area (Fig. 2) and it provides, as far as is known, the only winter data of this type in the Northwater. The mooring consisted of three current meters, at depths of 174, 324 and 531 m. Records include velocity, temperature and conductivity (salinity). During the period from October 1985 to August 1986, all the meters showed a monotonic increase in monthly mean temperature, to a maximum in February–March, followed by a monotonic decrease until August. The increase was from -0.70 to $+0.19^{\circ}\text{C}$ at 174 m, -0.29 to $+0.40^{\circ}\text{C}$ at 324 m and -0.31 to -0.02°C at 531 m. The two upper current meters, which were at the most interesting depths with respect to the “warm” water (Fig. 5), show a corresponding small cyclic salinity change peaking in February with mean speeds of $8\text{--}10\text{ cm s}^{-1}$ throughout the year. Although it is quite improbable that these current measurements can be applied directly to our 1991 data, the annual temperature cycle recorded in 1985–86 supports the above hypothesis that there is a seasonal entry of the West Greenland Current into the area, peaking in late February. Within the context of the hypothesis, it is possible to do a thumbnail calculation of the heat available from the inflowing warm water, the major uncertainty being the width to ascribe to the inflow and the general applicability of the available velocity measurements. Nevertheless, if the flow is assumed to be 20 km wide, it could contribute the major source of heat required to keep the polynya open in winter/spring. As seen below, biological observations in the surface layer are consistent with the proposed physical mechanism.

4.2. Phytoplankton

In the Northwater Polynya, maximum concentrations of Chl *a* were observed at station 4, where the individual values ranged between 14.9 and 19.5 mg m⁻³ and the areal concentration was 506 mg m⁻². Although very high, these values are not unique and

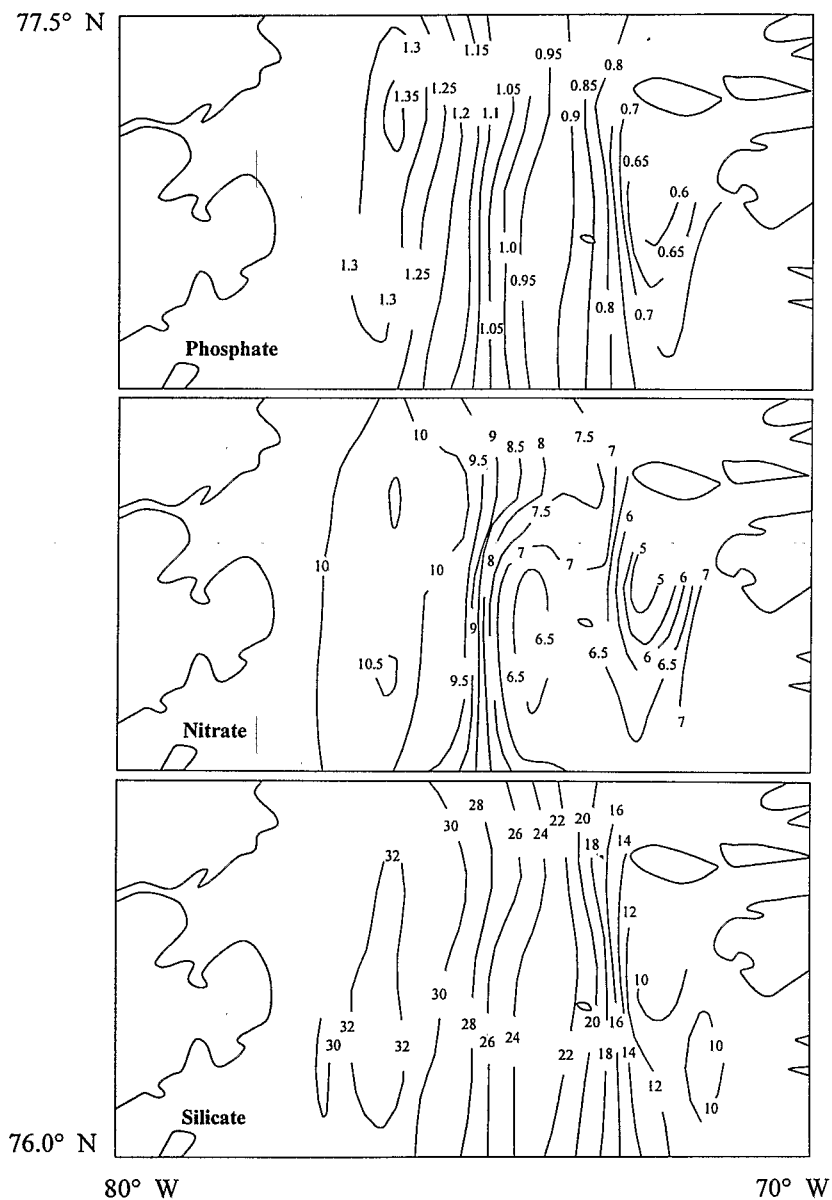


Fig. 7. Average concentrations of dissolved inorganic nutrients (mmol m⁻³) in the upper 30 m.

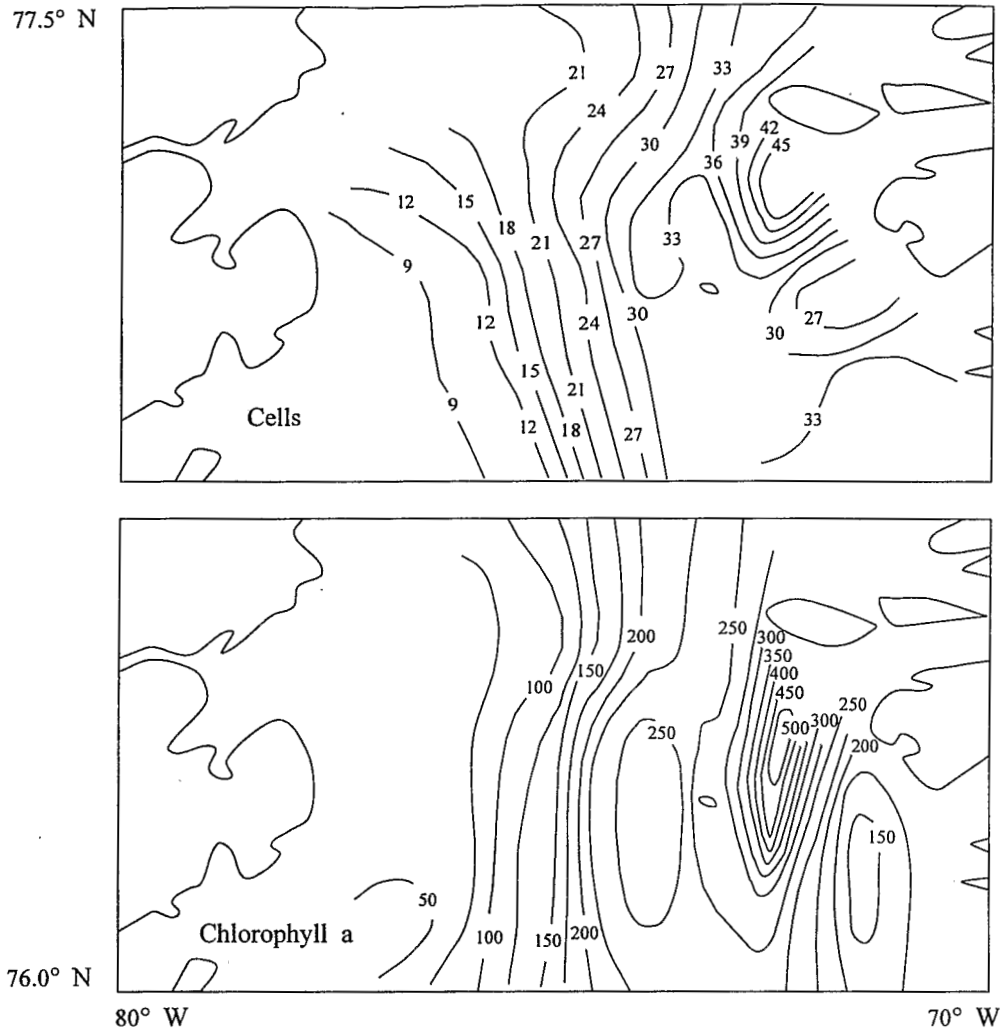


Fig. 8. Areal concentrations of phytoplankton cells (10^9 m^{-2}) and Chla (mg m^{-2}) in the upper 30 m.

similar or higher concentrations have been reported near the marginal ice zone in polar waters. For example, in the East Greenland Sea, there were high Chla concentrations (up to 15.6 mg m^{-3} , and *ca.* $200\text{--}260 \text{ mg m}^{-2}$ in the upper 30 m; Smith *et al.*, 1985) in the region of an eddy, where the absence of nutrient depletion suggested advective effects (Smith *et al.*, 1985). In the eastern Bering Sea, there was a strong pycnocline at *ca.* 30 m (Alexander and Niebauer, 1981), above which Chla was up to $>30 \text{ mg m}^{-3}$ (Figs 2 and 3 of Alexander and Niebauer, 1981) and the mean concentration in the upper 30 m was 455 mg m^{-2} (Table 1 of Smith *et al.*, 1985). In the Gerlache Strait (near the Antarctic Peninsula, south of Drake Passage), Chla values were up to 25 mg m^{-3} in January and the areal (0–50 m) concentrations were $>700 \text{ mg m}^{-2}$ in December and $>500 \text{ mg m}^{-2}$ in January (Holm-Hansen and Mitchell, 1991). All these values are comparable to those observed in the

Northwater at the same season. Ratios POC:PON (6 to ≥ 14) and POC:Chla (40 to ≥ 200) were normal. Cellular concentrations of Chla ranged from 2.3 to 10.7 $\mu\text{g cell}^{-1}$, which is high for water column diatoms but is consistent with values reported by Barlow *et al.* (1988) for the algal assemblage (largely dominated by diatoms) from the ice-water interface in Hudson Bay (Canadian Arctic; *ca.* 5–10 $\mu\text{g Chla cell}^{-1}$). Given the fact that the surface mixed layer often extended down to only *ca.* 30 m, values in Fig. 8 may be representative of the true areal concentrations at the time of sampling.

Ratios of elements in the dissolved inorganic nutrients indicate that phytoplankton growth was potentially limited by nitrogen at all stations (average N:P < 15 and N:Si < 1) and by silicon at the four easternmost ones (average Si:P ≤ 15 , at stations 1–4). Areal concentrations of Chla were inversely related to the average concentrations of the three nutrients in the 0–30 m layer (Fig. 9). It is interesting to note that, at stations 1 and 2, ratios N:Si (average *ca.* 0.8) were higher than at all other stations (from 0.6 to 0.2) and that, when

Table 2. Minimum and maximum (areal or average) concentrations of nutrients and phytoplankton and range of lowest and highest POC:PON and POC:Chla ratios (at individual depths), with station numbers in brackets

Variables	Minimum	Maximum
Phosphate (mmol m^{-3})	0.5 (4)	1.4 (8, 13)
Nitrate (mmol m^{-3})	3.7 (4)	10.8 (13)
Silicate (mmol m^{-3})	6.8 (4)	34.2 (13)
Chla (mg m^{-3})	1.7 (15)	16.9 (4)
Chla (mg m^{-2})	50 (15)	506 (4)
Cell numbers ($10^9 \text{ cells m}^{-2}$)	7.3 (13)	47 (4)
POC:PON (mass:mass)	6–7 (3–5)	15–21 (7–8, 12–15)
POC:Chla (mass:mass)	40–50 (4)	240–510 (7–8, 12–15)

Table 3. Average areal concentrations ($10^9 \text{ cells m}^{-2}$) and corresponding percentages (in brackets) of the various phytoplankton taxa in the three clusters of stations (see Fig. 2)

Taxa	Stations 1–5 and 10–11	Stations 6–8 and 12	Stations 13–15
Centric diatoms			
<i>Chaetoceros</i> spp.	4.1 (11)	3.9 (17)	2.7 (30)
<i>Melosira</i> spp.	1.7 (4)	0.7 (3)	0.5 (5)
<i>Thalassiosira</i> spp.	1.1 (3)	0.3 (1)	0.1 (1)
Other centric diatoms	10.2 (27)	10.5 (47)	2.7 (30)
Pennate diatoms			
<i>Fragilaria</i> spp.	0.5 (1)	0.0 (0)	0.0 (0)
<i>Navicula</i> spp.	15.3 (41)	4.3 (19)	1.6 (17)
<i>Nitzschia</i> spp.	0.5 (1)	0.3 (1)	0.2 (2)
Other pennate diatoms	2.3 (6)	1.6 (7)	0.4 (5)
Centric diatoms (total)	17.1 (46)	15.4 (68)	6.0 (65)
Pennate diatoms (total)	18.6 (50)	6.2 (28)	2.2 (24)
Dinoflagellates	1.5 (4)	0.8 (3)	0.9 (10)
Others	0.2 (1)	0.1 (1)	0.1 (1)
Total	37.4	22.5	9.2

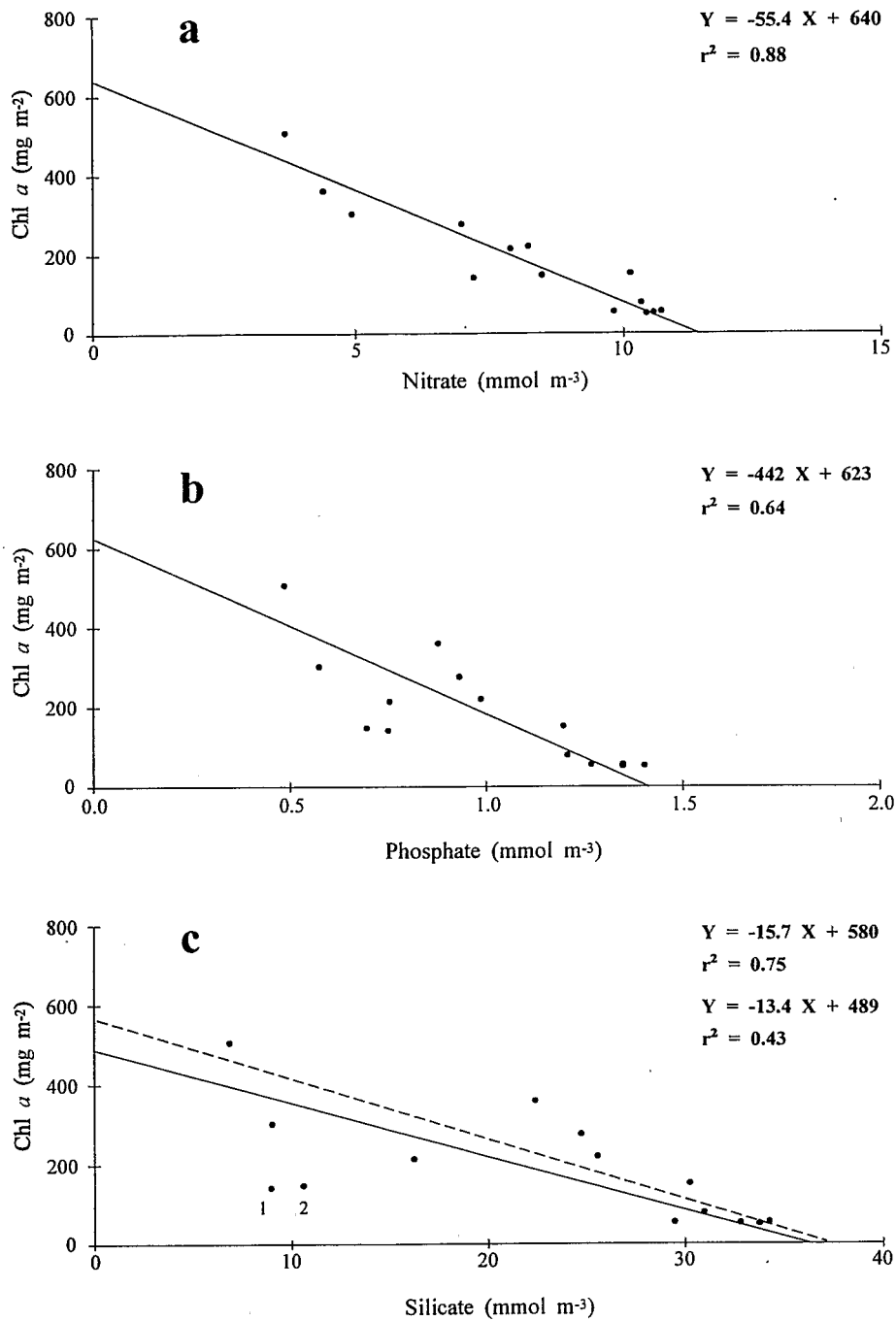


Fig. 9. Areal Chl a vs average dissolved inorganic nutrients in the upper 30 m. Coefficients of determination (r^2) and Model II linear regressions (Sokal and Rohlf, 1981). For silicate, computations include (solid line) or not (dashed line) the values from stations 1 and 2. The number of observations being $n = 14$, $r^2 > 0.44$ correspond to correlations with $p < 0.01$.

these two stations are removed from the regression of Chla on silicate (Fig. 9), the resulting r^2 and Y-intercept became similar to those computed for the other two nutrients. This supports the possibility of silicon deficiency, already derived from the Si:P ratios for stations 1–4. The fact that the three nutrients did yield similar potential maximum biomasses (Fig. 9) suggests that there was no major imbalance in nutrients, except perhaps at stations 1 and 2 for Si.

The highest average Chla concentrations, at station 4 (Fig. 9), corresponded to minimum average nutrient concentrations, i.e. silicate 6.8, phosphate 0.5 and nitrate 3.7 mmol m^{-3} . In the Gerlache Passage (see earlier), Holm-Hansen and Mitchell (1991; their Fig. 8) observed, at times of maximum Chla biomasses in December ($>700 \text{ mg Chla m}^{-2}$) and January ($>500 \text{ mg Chla m}^{-2}$), average concentrations (0–50 m) of phosphate *ca.* 1.0 and $>0.5 \text{ mmol m}^{-3}$, respectively, and nitrate *ca.* 15 and 5 mmol m^{-3} , respectively. Their values for January are of the same order as those in our Fig. 9. These authors remarked that Chla concentrations up to 25 mg m^{-3} , observed in January, are close to the maximum biomass that can be produced by Antarctic phytoplankton when grazing pressure is reduced (Sakshaug and Holm-Hansen, 1986) and that the correspondingly low nutrient concentrations were approaching the level at which nutrient limitation of growth might ensue. The same may have been true at the easternmost stations in the Northwater, at the time of sampling. This would be consistent with indications of possible silicon limitation, derived above from the Si:P and N:Si ratios.

The Y-intercepts of regressions in Fig. 9 provide estimates of maximum biomass, based on nutrient exhaustion. Using this approach, the potential maximum biomass in the upper 30 m would be *ca.* 600 mg Chla m^{-2} , or lower if there was silicon limitation (Fig. 9c). The actual value at station 4 (i.e. 506 mg Chla m^{-2}) was close to the potential maximum derived from Fig. 9. Another way to approach the same question is to use the X-intercepts of the regression as estimates of the initial stocks of nutrients (i.e. 11.6 mg-at N m^{-3} , 1.4 mg-at P m^{-3} and 1.4 mg-at Si m^{-3}) and to multiply them by 30 m, by the appropriate Redfield ratio (i.e. C:N = 6.6, C:P = 106, and C:Si = 7.1; Redfield, 1958; Redfield *et al.*, 1963) and by 12 $\text{mg mg-at}^{-1} \text{ C}$, and divide the results by C:Chla = 40 $\text{mg C mg}^{-1} \text{ Chla}$, to obtain potential Chla biomasses corresponding to the initial stocks. Resulting values are 690 mg Chla m^{-2} for N and >1000 for P and Si; the first value is similar to the Y-intercepts for the three regressions. The lower value for N indicates that the final biomass of phytoplankton could have been limited by the availability of N. The similarity between the potential biomass derived from the initial N stock and those from the regressions suggests that, since the beginning of the bloom, there had been either no replenishment of the initial N stock or a near balance between N replenishment and export (by grazing and sedimentation).

There was a striking parallelism between the horizontal distribution of temperature above freezing at surface (Fig. 4) and the distribution of nutrients (Fig. 7) and phytoplankton (Fig. 8). Relationships with the physical variable were inverse for the former and direct for the latter. Temperature above freezing at surface accounted for a large fraction of the variation (r^2) in the concentrations of nitrate (0.59), phosphate (0.81), silicate (0.76), Chla (0.58) and phytoplankton cells (0.64) in the upper 30 m. The direct relationship between temperature above freezing at surface and phytoplankton suggests that the spring bloom was triggered by the absence of sea ice. In polar regions, pennate diatoms generally dominate the ice algal assemblages (e.g. Horner, 1985), so that their westward decrease in both numbers and proportions (Table 3) could indicate that phytoplankton were, at least partly, seeded by the ice algae released in the water column.

Other studies reached the same conclusion, based on either similarities between species from the ice and in the water column (e.g. Schandelmeier and Alexander, 1981, for the Arctic; Smith and Nelson, 1985, 1986, and Garrison *et al.*, 1987, for the Antarctic) or laboratory experiments with sea ice algae (e.g. Kuosa *et al.*, 1992).

The overall picture in the Northwater Polynya at mid-May was that of a diatom bloom, moving westward and progressively exhausting the nutrients. Initiation of the bloom appeared to have been linked to the absence of sea ice. A source of heat for this would have been the sensible-heat process described above.

Acknowledgements—The authors thank R. A. Cooke and J. A. Spry for assistance at sea, M. Parrot, J. Richard and M. Parent for laboratory analyses and one anonymous referee for useful suggestions. Funds for the charter of the MV *Arctic* as well as equipment and personnel for physical oceanographic observations were provided by the Department of Fisheries and Oceans (Institute of Ocean Sciences). The biological component of the study was funded by grants to one of the authors (L.L.) from the Natural Sciences and Engineering Research Council of Canada and to GIROQ from NSERC and the Fonds FCAR of Québec. The cruise would not have been possible without the full co-operation of Capt. D. Millar and the crew of the MV *Arctic* and of the Canarctic Corp. Contribution to the programme of GIROQ (Groupe interuniversitaire de recherches océanographiques du Québec).

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