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Phytoplankton Chlorophyll Distribution in the Eastern Canadian Arctic

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ABSTRACT. The distribution of phytoplankton chlorophyll concentration in Jones Sound, Lancaster Sound, and Eastern Baffin Bay was studied during the period 16-27 August 1979, using continuous ship-based horizontal and vertical profiling and continuous aerial water colour measurements. These data are discussed in relation to physical data collected from the ship, and to infrared temperature measurements made from the aircraft and the TIROS series satellites.

While the satellite and airborne remote sensing techniques are capable only of viewing the near-surface layer, they provided a much more detailed and synoptic coverage of this large area than was possible using a vessel alone. Together the three types of data provide a reasonably detailed picture of phytoplankton distribution which compares well with other physical oceanographic data.

On average the chlorophyll standing crop was moderate (69 $mg \cdot m^{-2}$ in the top 35 m, n=24) and comparable to that reported for other open-water arctic regions, but the phytoplankton were not evenly distributed vertically or geographically. In Jones Sound and Lancaster Sound where local ice melt reduced the surface water density, strong subsurface chlorophyll maxima (up to 18 $mg \cdot m^{-3}$ in a 1 m thick layer) were observed in association with the pycnocline. At the mouths of these sounds and along the eastern coast of Devon, Bylot, and Baffin islands the phytoplankton distribution was more vertically homogeneous and closely linked to the physical structure of the Baffin Current. Highest pigment concentrations were associated with eddies or meanders in the current. It is possible that these localized pigment concentrations are one manifestation of "biological hotspots" which help feed the large populations of marine birds and mammals of the eastern Arctic.

Key words: phytoplankton, chlorophyll, distribution, eastern Canadian Arctic, remote sensing

RÉSUMÉ. L'article étudie la distribution de concentrations de chlorophylle de phytoplancton dans le détroit de Jones, le détroit de Lancaster et l'est de la baie Baffin, durant la période entre les 16 et 27 août 1979, au moyen de profils horizontaux et verticaux continus effectués à bord du navire et du mesurage aérien continu de la couleur de l'eau. Ces données sont discutées par rapport aux données physiques recueillies par le navire et aux mesures infrarouges de la température prises de l'avion et des satellites de la série TIROS.

Bien que la satellite et les techniques aéroportées de télédétection ne peuvent discerner que la couche près de la surface, elles permettent un traitement plus détaillé et synoptique de cette grande région que ne l'était possible avec seul le vaisseau. Une fois rassemblés, les trois types de données présentent un tableau suffisamment détaillé de la distribution du phytoplancton qui est relativement comparable à d'autres données physiques océanographiques.

En moyenne, la quantité de chlorophylle actif était modéré (69 $mg \cdot m^{-2}$ dans les 35 m supérieurs, n=24) et était comparable à la quantité signalée dans les autres régions arctiques d'eau libre, tandis que le phytoplancton indiquait une distribution inégale, tant sur le plan vertical que géographique. Dans les détroits de Jones et de Lancaster, où la fonte de glace locale réduit la densité de l'eau de surface, des quantités maximales élevées de chlorophylle sous la surface de l'eau (atteignant $18 \cdot m^{-3}$ dans une couche d'1m d'épaisseur) furent observées en association avec la pycnocline. A l'entrée de ces détroits et le long de la côte est des îles Devon, Bylot et Baffin, la distribution de phytoplancton était plus homogène sur le plan vertical et était étroitement reliée à la structure physique du courant de Baffin. Les concentrations de pigments les plus élevées étaient associées à des remous et des méandres dans le courant. Ces concentrations localisées de pigments sont peut-être une manifestation des "points rouges biologiques" qui aident à l'alimentation de larges populations d'oiseaux et de mammifères marins dans l'est de l'Arctique.

Mots clés: phytoplancton, chlorophylle, distribution, l'est de l'Arctique canadien, télédétection

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INTRODUCTION

The eastern end of Lancaster Sound and the western side of northern Baffin Bay along the coasts of Devon, Bylot, and Baffin islands have been described as one of the most productive marine areas in the Canadian Arctic (Nettleship and Smith, 1975; Milne and Smiley, 1978; Thomson, 1982) because of the high benthic biomass and the very large seabird populations which nest in the area.

We report here on an exploratory survey of the chlorophyll *a* distribution over northwestern Baffin Bay, Jones Sound, and Lancaster Sound during the period of maximum open water in late August 1979. We describe the distribution of chlorophyll *a* (hereafter referred to only as chlorophyll) and surface temperature as measured from a ship and an aircraft, and discuss these in the context of physical oceanographic observations made at the same time (Fissel *et al.*, 1982).

Sekerak *et al.* (1979) have also studied the plankton of this area, but their stations were widely separated in both time and space, so that information on geographic distribution was degraded by temporal variations. Until recently, this has been a problem for studies of large or dynamic areas, because of the impossibility of synoptic sampling. Development of continuous underway measurement techniques (Denman, 1976) have helped to reduce the problem. Progress in remote sensing technology now makes it possible to use aircraft and satellites to supplement ships in mapping the distribution of chlorophyll and temperature (Gordon *et al.*, 1983; Chamberlin, 1982). The rapid and two-dimensional spatial coverage is a powerful tool for describing the spatial scales, localizing flows, and resolving complicated eddy fields. Combined with *in situ* sampling and vertical profiling from ships, a more complete picture of distributions over large areas can be constructed.

Remote measurement of surface temperature from either aircraft or satellites involves detection and measurement of

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thermal infrared radiation in the 8-14 micron region of the electromagnetic spectrum. Typically, remotely-derived sea surface temperatures, after appropriate correction for atmospheric effects, agree with conventionally observed surface or 1-m temperatures to within about $\pm .5$ °C except where the sea is very calm and insolation is very high (Tabata and Gower, 1980). Remote assessment of phytoplankton takes advantage of the spectral variations of light leaving the sea surface (the water colour) when different concentrations of phytoplankton are present. Because water absorbs only weakly at blue wavelengths, pure water appears blue to an observer. By contrast, phytoplankton strongly absorbs blue light, and increasing amounts of pigment cause the water colour to shift from blue to green. A measure of the ratio of green to blue water-leaving radiance (G/B) can be shown to relate closely to the chlorophyll concentration in the upper 5 m of the water column (Clarke *et al.*, 1970; Clark, 1981; Gordon *et al.*, 1983). A second index of near-surface phytoplankton concentrations may be derived from the water colour by measuring *in vivo* fluorescence of chlorophyll and its phaeopigments. This adds a Gaussian shaped peak near 685 nanometres (nm) to water reflectance spectra (Neville and Gower, 1977; Gower, 1980; Borstad *et al.*, 1981). Because of greater absorption in water of this longer wavelength, red light, the height of this fluorescence line (the FLH signal) is sensitive to the chlorophyll in the uppermost 2 m of the water column (Gordon, 1979).

METHODS

Ship Survey

The ship survey was conducted from the MV *Theron* during the 11-day period 16 August-27 August 1979, along a cruise track of approximately 2900 km as shown in Figures 1 and 2. Sea surface temperature data were collected via bucket thermometer at regular intervals throughout the cruise as part of meteorological observations. The concentration of surface layer (defined here as the upper 4 m) chlorophyll was monitored along the entire cruise track using continuous flow-through fluorometry with frequent discrete samples taken for calibration. Sea water was supplied to a Turner Designs Model 10 fluorometer via the ship's seawater system which drew water from a depth of 3 m. Because of a reservoir in the seawater system, the fluorescence signal was averaged over 1 or 2 km.

At 28 locations throughout the study area, continuous vertical pumped profiles of chlorophyll *in vivo* fluorescence, and at some stations temperature, were obtained from the surface to 25 or 35 m depth. For complete sampling of the euphotic zone at all stations, vertical profiling should have continued to below 50 m, but this was not possible because of limited ship time. Since our hose was lowered by hand, the weight of the hose assembly and drift of the vessel determined the maximum depth of any profile. At three or more depths on each profile, discrete samples were measured to determine amount of extracted chlorophyll, dry weight of total particulate material, and light absorption by dissolved organic matter (D.O.M.), and phytoplankton species composition was examined. Secchi

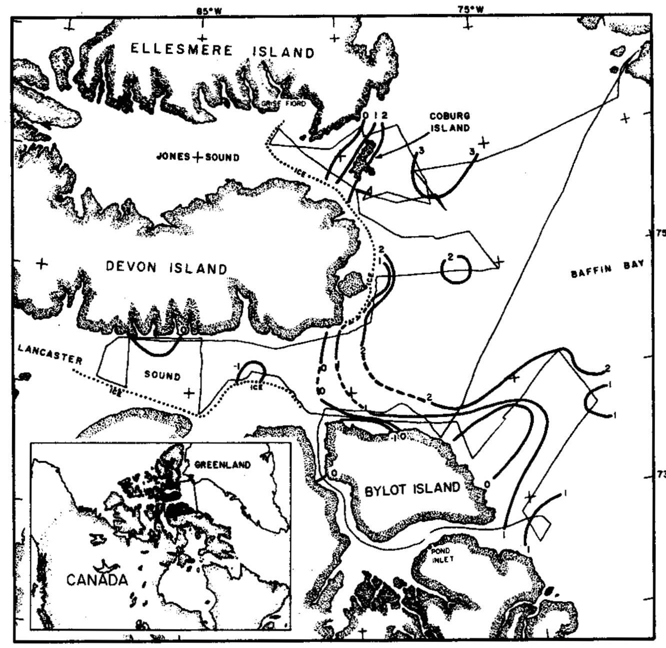

FIG. 1. Sea surface temperature (°C) as observed by bucket observations from MV *Theron* during the period 16-27 August 1979. Inset shows location of study area within the Canadian Arctic.

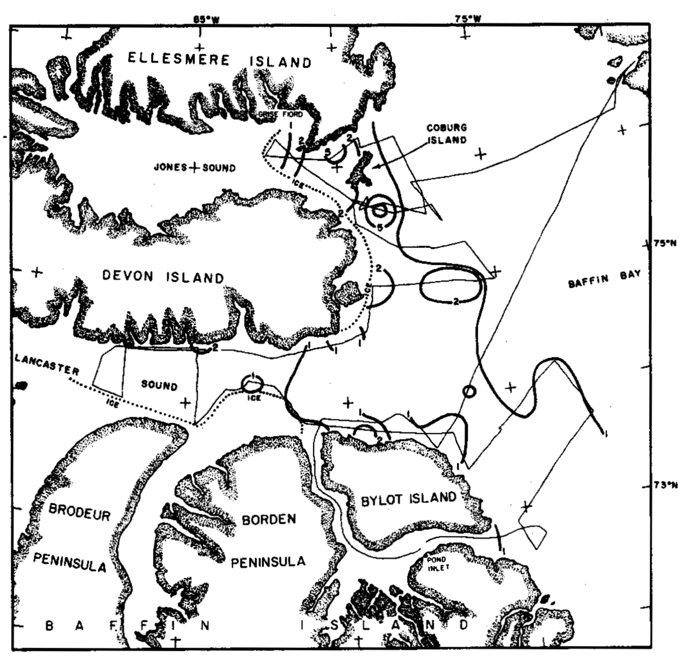

FIG. 2. Surface layer chlorophyll concentration ($mg \cdot m^{-3}$) observed from MV *Theron* during the period 16-27 August 1979. Discrete samples taken from the surface (bucket), 1 m depth (pumped and hydrocast samples), and 3 m depth (ship's seawater intake) are included. Boundaries between zones are based on continuous *in vivo* fluorescence records.

transparency was recorded at those stations visited during daylight hours. At these and other stations, vertical conductivity-temperature-depth (CTD) profiles of temperature, salinity, and calculated density were made by Fissel *et al.* (1980). At most stations the *in vivo* fluorescence cast was made within half an hour of the CTD cast. Chlorophyll data collected as part of other studies (A. Sekerak, LGL Ltd., pers. comm. 1980, J. Bunch, Arctic Biological Station, pers. comm. 1980) were used to supplement our own data.

For the work reported here, chlorophyll and phaeopigment concentrations of discrete samples (n = 164) were measured using the fluorometric technique of Strickland and Parsons (1972). Total suspended particulate material was measured for 34 samples at 11 stations, also according to the methods of Strickland and Parsons (1972), but did not include combustion or peroxide treatment. Phytoplankton are therefore a large component of the total suspended material.

The importance and distribution of dissolved organic material (which absorbs strongly at short wavelengths and therefore interferes with interpretation of the water colour signal) were assessed by measuring the optical density at 350 nm of the filtrate from the particulate matter filtrations (Bricaud *et al.*, 1981). Filtrate samples were preserved with $HgCl_2$ to prevent bacterial growth during the one-month storage period. Phytoplankton samples from the surface or 1 m depth and from the subsurface fluorescence maxima were obtained from 12 locations. Samples were preserved with Lugol's iodine and enumerations and identifications of all species in the near-surface samples were made using standard methods.

Airborne Survey

Airborne surveys totalling approximately 2500 km were carried out on 24, 25, 26, and 27 August 1979 using a deHavilland Twin Otter aircraft with Omega VFL navigation (Figs. 3, 4, 5). Flight scheduling was severely affected by weather and demands for aircraft time by other users. Low ceilings with occasional snow and fog limited our choice of altitude throughout the survey period; normal flying altitude was 150 m, and minimum safe altitude was 90 m because of the presence of icebergs. Flight lines avoided ice-covered areas, although the response of both the radiometer and the spectrometer allowed

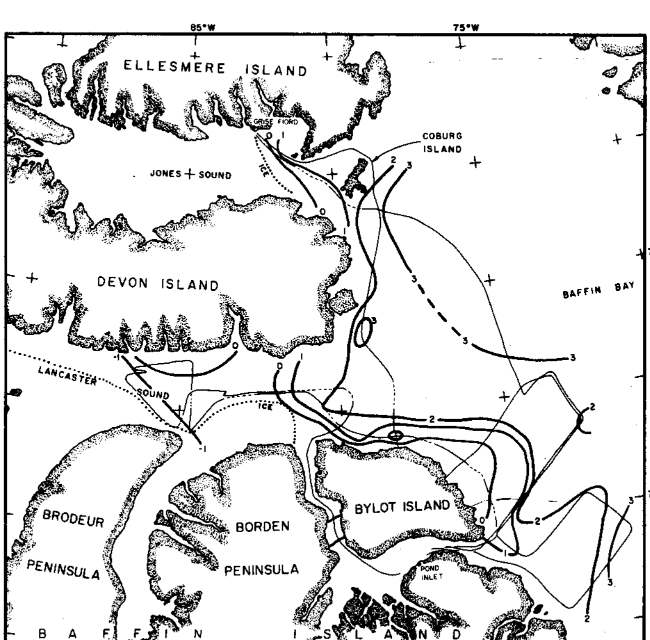

FIG. 3. Sea surface temperatures (°C) from airborne infrared radiometer measurements during the period 24-27 August 1979.

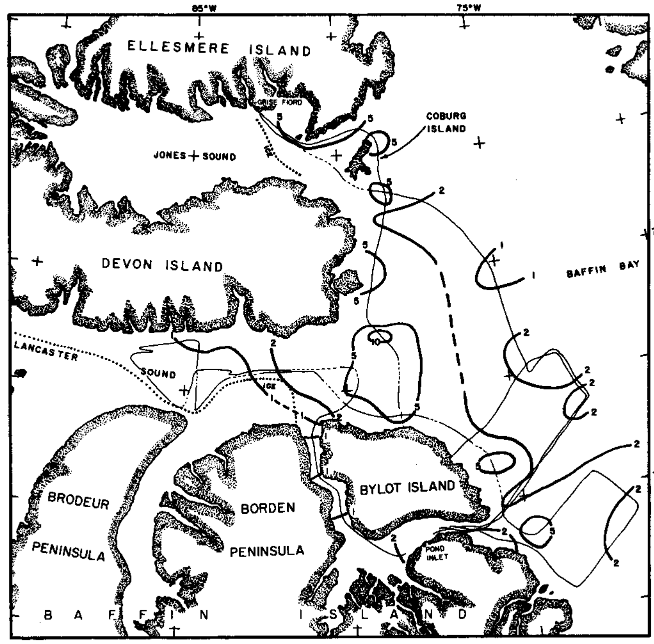

FIG. 4. Surface chlorophyll concentration ($mg \cdot m^{-3}$) inferred from airborne measurements of fluorescence line height (FLH) during the period 24-27 August 1979.

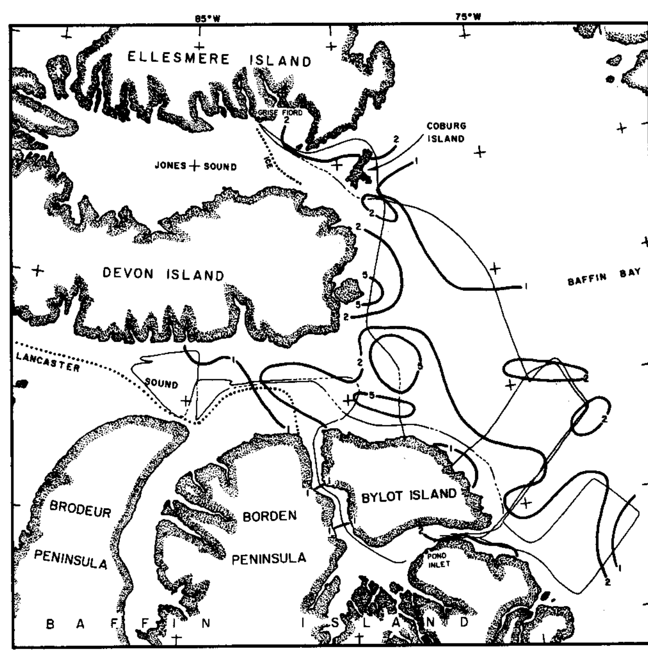

FIG. 5. Surface chlorophyll concentration ($mg \cdot m^{-3}$) as inferred from measurements of the green /blue reflectance ratio (G/B) during the period 24-27 August 1979.

observations in open leads wider than about 150 m.

Aerial measurements of sea surface temperature and near-surface chlorophyll *a* concentration were made using a Barnes PRT-5 radiation thermometer and the Institute of Ocean Sciences (IOS) 256-channel colour spectrometer respectively. The PRT-5 is a simple commercial infrared radiometer that measures the 10-12 μ thermal radiation from the ocean using a chopped, temperature-stabilized thermistor. The instrument has a 2° field of view and precision of about 0.1 °C; however, atmospheric absorption in fog or mist, and in certain situations reflection from the water surface, can produce errors of up to a degree.

The IOS spectrometer (Walker *et al.*, 1974, 1975) uses a reflection grating and an array of silicon diodes to measure and record the spectral variations of light leaving the sea surface. Reflectance spectra were computed by normalizing the radiance upwelling from the sea surface (L_u) by the downwelling irradiance (E_d) on a horizontal opal glass collector on the top surface of the aircraft fuselage. The reflectance ratio (L_u/E_d) thus formed is thereby adjusted to account for cloud along the flight path. The spectrum of the incident irradiance was measured frequently using a light-pipe connection to the spectrometer, and its intensity was monitored continuously by two silicon diodes.

The reflectance spectra were corrected for a mean atmospheric scattering contribution appropriate to the aircraft altitude, and for an additive signal from surface reflection, mist, or whitecaps which was assumed to be white and of a magnitude such that the corrected water reflectance at 780 nm was made equal to zero. The continuous computations of the two chlorophyll indices so corrected were then averaged over 1-min intervals (approximately 5 km) and plotted as chart overlays using a Calcomp plotter. The indices were converted to chlorophyll values using calibrations derived from experiments off the British Columbia coast (Gower and Borstad, 1981) since it proved impossible to make repeated overflights of the ship during this exercise. We have since observed variations of a factor 2 on each side of the mean proportionality constant used to relate FLH to chlorophyll. The G/B ratio calibration is also based largely on the water spectra observations off the British Columbia coast which show a roughly similar scatter. In this case, however, the large body of data collected by other observers, especially in connection with the NIMBUS-7 Coastal Zone Colour Scanner programme (Clark, 1981), is consistent with the values used here. Further details of the measurements and techniques for airborne data analysis can be found in Gower (1980), Borstad and Brown (1981), and Gower and Borstad (1981).

Satellite Imagery

Three thermal infrared images of the study area (Figs. 6, 7, 8) were acquired by the Advanced Very High Resolution Radiometer (AVHRR) on the TIROS-N spacecraft during a relatively cloud-free period in the week preceeding the ship-based data collection. This imagery, obtained in photographic form from the Environmental Data Information Service, Washington, D.C., has not been corrected geometrically or for atmospheric or cloud effects. Nevertheless, considerable oceanographic information is evident in the sea surface temperature patterns. Colder temperatures are shown as lighter tones in these images, and warmer (snow-free) land appears dark. Very light tones are clearly due to high-level, low-temperature clouds. Low-level clouds have temperatures comparable to the colder water in the area and can only be distinguished by their transience when comparing Figures 6, 7, and 8. Ice covered large areas of the sounds between the Arctic Islands at the time of our survey and would have covered a rather larger area at the time the satellite images were made. Because the thermal contrast between melting ice and the surface meltwater layer is low, the lightest water tones in the images can only indicate that some mixture of the two is present. Digital processing, using data from the visible channel, would permit one to "mask" cloud and ice, thereby reducing these ambiguities. Within these limitations, an interpretation of Figures 6a, 7a, and 8a, making use of the associated visible images, is presented in Figures 6b, 7b, and 8b. Areas

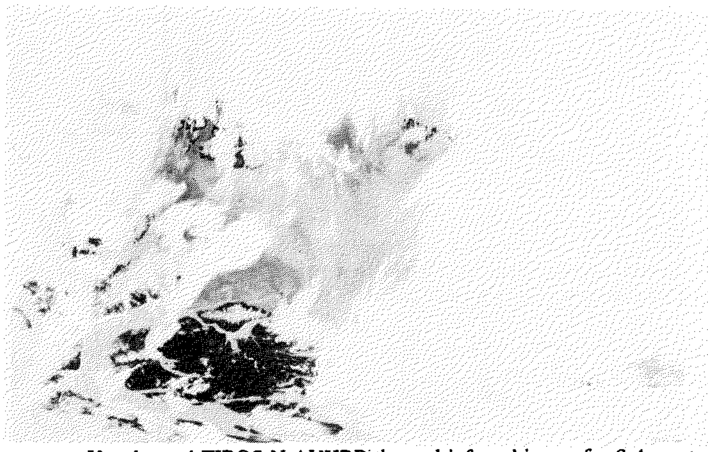

FIG. 6a. Unenhanced TIROS-N AVHRR thermal infrared image for 8 August 1979. Coldest temperatures (high-level cloud) are shown as lightest shades, warmest snow-free land areas are black. Low-level fog and cloud having temperatures similar to that of the sea are distinguished from in-water structure by using the associated visible images and by their shape and movement from one image to another. Complex eddy structure is visible in the clear area north and east of Bylot Island.

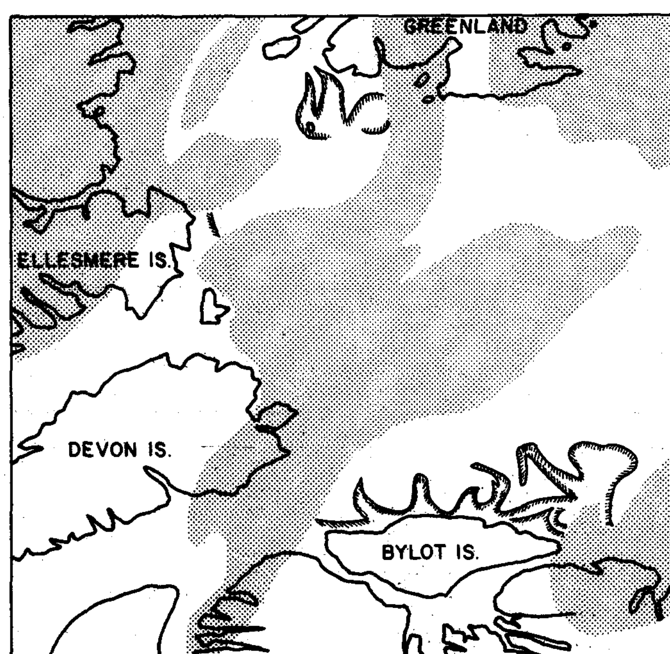

FIG. 6b. Interpretation of Figure 6a showing apparent thermal fronts in the ocean as solid lines with hatching on the colder side. Areas obscured by cloud as seen in the associated visible imagery are stippled.

obscured by cloud are shaded, and apparent oceanographic fronts are indicated by solid lines with hatching on the colder side.

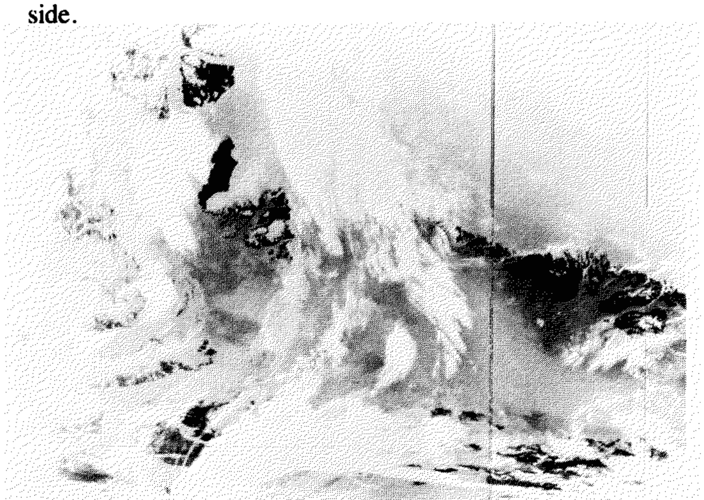

FIG. 7a. Unenhanced TIROS-N AVHRR thermal infrared image for 10 August 1979. Eddy-like disturbances are visible along the temperature boundary marking the edge of the Baffin Current east of Ellesmere and Devon islands. Cloud and low-level fog cover the entrance to Lancaster Sound.

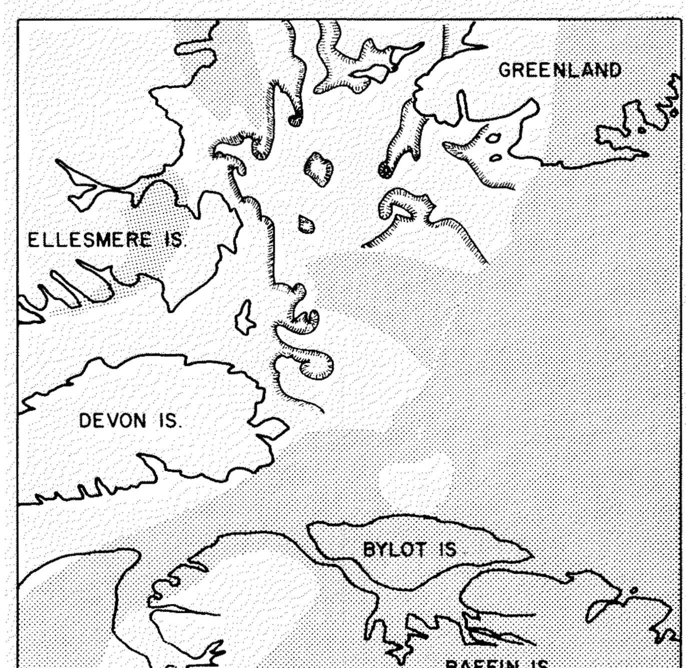

FIG. 7b. Interpretation of Figure 7a. Same scheme as Figure 6.

FIG. 8a. Unenhanced TIROS-N AVHRR thermal infrared image for 12 August 1979. Disturbances are again visible along the temperature boundary marking the edge of the Baffin Current east of Ellesmere Island, and an anti-cyclonic eddy is evident off northeast Devon Island. Note the position of the intrusive current front across Lancaster Sound and along the north coast of Bylot Island. Eddies east of Bylot Island are largely obscured by cloud.

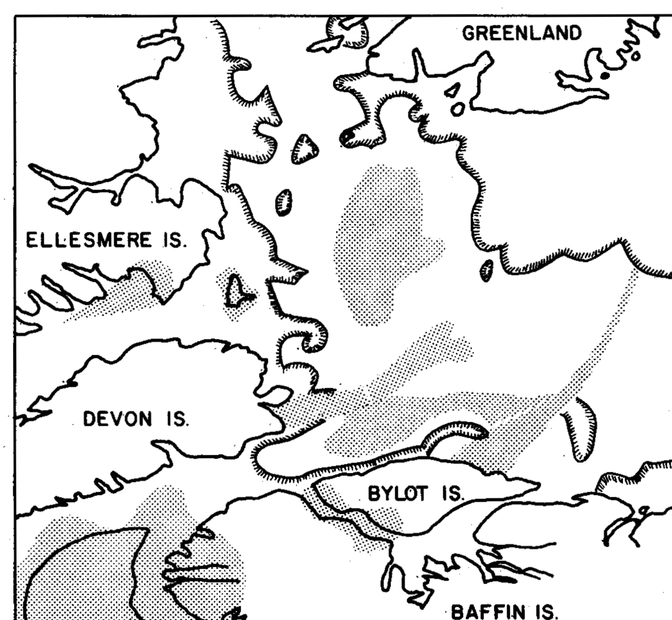

FIG. 8b. Interpretation of Figure 8a. Same scheme as Figures 6 and 7.

RESULTS

Temperature

Ship bucket temperatures (Fig. 1) and airborne radiometric measurements (Fig. 3) both showed the coldest waters to be in Jones Sound and Lancaster Sound near pack ice, and along northern and eastern Bylot Island. A broad thermal front separated this cold water from warmer water offshore in Baffin Bay and across the mouth of Lancaster Sound. A narrow tongue of cold water extended from Lancaster Sound eastward along the north coast of Bylot Island, then widened east of the island in an area of complicated isotherms.

The satellite images (Figs. 6, 7, 8) agree with the broad outline of thermal patterns seen from the ship and aircraft. However, while the ship and aircraft data are for a relatively few points and intersecting transects, the satellite data show considerably more spatial detail, allowing identification of several eddies east of the sharp thermal discontinuity separating the cold Baffin Current from the offshore water. The satellite-derived imagery shows that the complicated isotherms in the ship and aircraft data (Figs. 1, 3) east of Bylot Island were caused by eddying circulation in that area.

Surface Chlorophyll Distribution

Both the ship and the aircraft detected very little surface chlorophyll in northwest Baffin Bay and in Lancaster Sound north of Brodeur and Borden peninsulas. Greatest concentrations were found in a band from the mouth of Jones Sound south across Lancaster Sound and along the eastern coast of Bylot Island (Figs. 2, 4, 5). Small patches (10-15 km in diameter) of elevated chlorophyll concentration were encountered throughout this zone.

The range of chlorophyll values observed in representative areas covered by both the ship and aircraft are listed in Table 1. Many of the differences are to be expected since the surveys were not made simultaneously, and the ship and aircraft tracks differed considerably. Ideally, remote sensing experiments should include a series of coincident measurements over a surface vessel, so as to provide pairs of observations over the full range of measured chlorophyll concentrations and local environmental conditions. This was not possible during our surveys because of limitations on our use of the aircraft, bad weather, and poor radio communications. We are therefore forced to use mean calibrations derived from experiments off the British Columbia coast (Gower, 1980; Borstad *et al.*, 1980). Table 1 shows that the agreement is good in areas such as Lancaster Sound where the time interval between ship and aircraft measurements was short, but that there is a tendency for the airborne values to be higher. A different calibration factor would remove this tendency, but we prefer to use a previously deduced mean value as discussed above.

Variations in the amount of *in vivo* (fluorometer) fluorescence per mg chlorophyll (fluorescence yield) are frequently reported in the literature (Strickland, 1968; Kiefer, 1973) and were also observed during this survey. It is reasonable to expect such variations to appear in remotely observed fluorescence (FLH). However, our observed fluorescence yield variations at the surface were less than a factor 2 and this is the maximum effect on FLH that we expect for the present survey.

D.O.M. absorption at 350 nm was less than $0.2 \cdot m^{-1}$ for all but one surface sample in the Jones Sound area. At the visible wavelengths used to calculate the G/B ratio, this would resemble about 2 mg chlorophyll$\cdot m^{-3}$. However, since we empirically derived the relationship between pigment concentration and G/B, it is the variations in D.O.M. absorption which will determine the potential error from this source ($\pm 1 mg \cdot m^{-3}$).

Measurements of total suspended particulate matter suggested that it was dominated by phytoplankton at the time of our surveys. This simplifies interpretation of the remotely sensed data since glacial flour and silt can be confused with phytoplankton.

Vertical Distribution of Chlorophyll and Fluorescence

The vertical distribution of chlorophyll concentrations, *in*

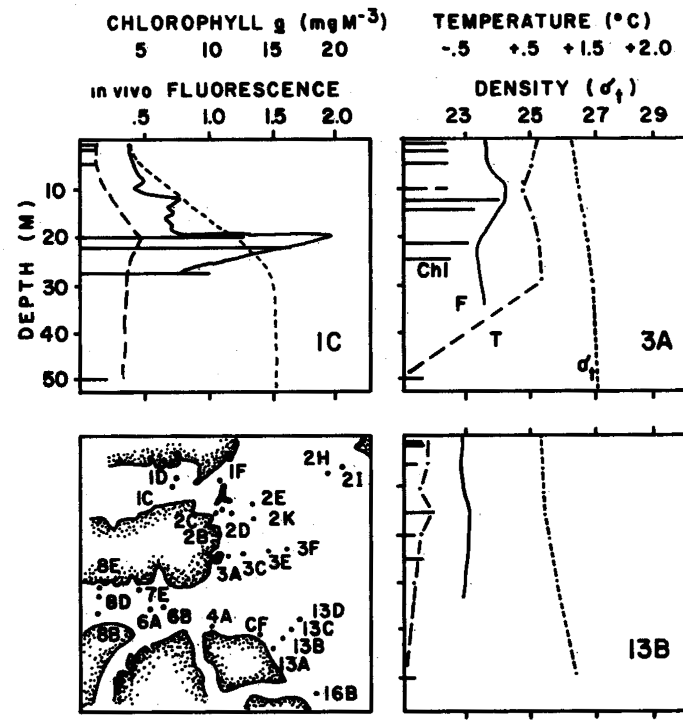

FIG. 9. (Lower left) Approximate location of ship stations where vertical profiles were obtained. (Upper row and lower right) Vertical distribution of chlorophyll *a*, *in vivo* fluorescence (———), temperature (— — —) and calculated sigma-T (·---·) at three representative stations. Concentrations of discrete samples are indicated by horizontal bars. Temperature and sigma-T for stations 3A and 13B are from CTD data tabulated for specific depths by Fissel *et al.* (1980) (dots on profiles). Profiles for 1C are based on our own continuous thermistor data (no dots).

TABLE 1. Comparison of chlorophyll estimates from ship and aircraft data from representative areas

Area	Time interval between ship and aircraft measurements	Concentration of extracted chlorophyll from ship samples	Estimate of chlorophyll concentrations from airborne observations	
			FLH	G/B
Central Lancaster Sound	0 days	0.1-1.7	0.1-1.8	0.4-1.8
E of Bylot Island	1-3 days	0.7-2.2	0.8-4.1	0.9-4.2
SE of Bylot Island	2 days	1.3-1.9	3.5-7.5	3.0-3.9
N of Bylot Island	1-9 days	0.6-2.0	2.3-3.7	2.7-4.2
E of Devon Island	4 days	1.6-3.2	4.0-5.7	1.5-5.5
Baffin Bay E of Devon Island	5 days	0.1-0.6	0.7-1.3	0.6-0.9
N Jones Sound	6 days	0.8-5.0	2.3-8.1	1.0-3.9
S of Coburg Island	6 days	0.7-5.0	2.0-6.3	0.8-3.7

vivo fluorescence (IVF), temperature, and calculated density (sigma-t) are summarized in Figure 9. Most stations in Baffin Bay were weakly stratified and had relatively homogeneous chlorophyll distributions. However, in Jones and Lancaster sounds, local ice melt had caused strong vertical density stratification, and subsurface chlorophyll maxima were found in or just below the pycnocline at 10 to 20 m depth. The strongest maxima were associated with the most stratified waters (coldest, lowest surface salinities).

The phaeopigment/chlorophyll ratio and fluorescence yield for samples from all of these maxima except station 1D were very low, suggesting that the phytoplankton at these depths were physiologically active and not senescent. Secchi transparency (15-16 m at Jones Sound stations, 20 m at station 8B in Lancaster Sound) indicate that the maxima were well within the euphotic zone.

Phytoplankton Species Composition

At 11 of the 12 stations for which surface phytoplankton samples were available, small unidentified microflagellates (1-10 μm) dominated the population, contributing between 30 and 98% of the total cells. At all stations except station 8, total cell number, number of species, and chlorophyll concentration tended to follow the percent contribution by diatoms (mg chlorophyll$\cdot$m^{-3} = 0.227 + 0.031 $\times$ (% diatoms); SE = 0.678; $r^2 = 0.48$; n = 11). In Jones Sound and around Coburg Island, diatoms of the centric genus *Chaetoceros* (principally *C. socialis*) made up 20-40% of the population. The large surface population at station 3A immediately east of Devon Island had proportionately more diatoms (69% of total cells) but this was a result of the contribution by pennate forms such as *Nitzschia cylindrus* and *N. grunowii* which were not present further north. In Lancaster Sound pennate diatoms comprised nearly 50% of the total cell numbers at 8B, with *Nitzschia delicatissima, N. seriata, N. cylindrus* and *N. grunowii* most important. Cells of *N. delicatissima*, which made up fully 29% of the total at 8B, were in very poor condition and probably contained low amounts of chlorophyll per cell.

A complete species list with cell numbers per litre is available from the authors or the Arctic Institute Library (Acreman, 1981).

DISCUSSION

A Summary of Surface Circulation

The main features of the surface circulation at the time of our survey are shown in Figure 10. As the Baffin Current flowed southward along the western side of Baffin Bay, it was joined by colder, fresher meltwater ~~from Jones~~ Sound. Satellite-tracked drogues indicated eddying circulation at the joining of these flows just south of Coburg Island. Southward along eastern Devon Island a large meander, which appears to have formed near the beginning of August, was well formed on the offshore edge of the coastal currents near 75°N. Further south, the Baffin Current narrowed and rounded southeastern Devon Island, entering the mouth of Lancaster Sound as an

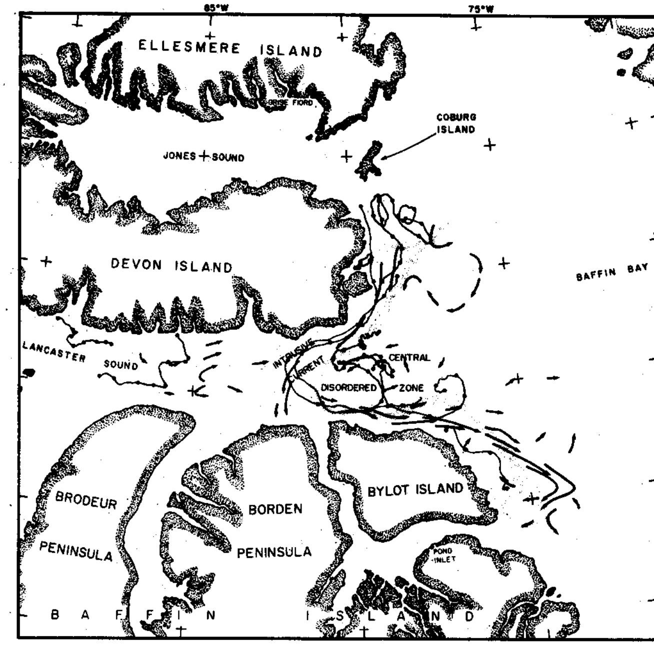

FIG. 10. Summary of surface circulation during the period 12-31 August 1979, as indicated by satellite tracked drifters and dynamic topography (composite prepared from data from Fissel *et al.*, 1980, 1982). The generalized locations of the boundaries between circulation zones are stippled.

"intrusive current". The flow then crossed to the southern side and left Lancaster Sound north of Bylot Island. Fissel *et al.* (1982:Fig. 22) showed that in Lancaster Sound this current is associated with strong fronts reflecting large horizontal density gradients, and decreased stratification which provides the means for enhanced vertical mixing.

To the east of the intrusive current, the circulation at the entrance to Lancaster Sound is generally disordered and irregular. Many drifters released east of Devon Island earlier in August spent several days in this zone before being carried further south. To the west of the current, in Lancaster Sound itself, the circulation was also slow and variable.

The Baffin Current exits Lancaster Sound along the north coast of Bylot Island as a jet, usually leaving the coast near 77°W. It often loses large amounts of energy in meanders and cyclonic eddies such as those visible on the satellite image (Fig. 6a) and in the drogue tracks for September (Fissel *et al.*, 1982). Only one drifter passed through this area during the time of our survey.

Relation of Surface Temperature and Chlorophyll Distribution to the Circulation

By late August, Baffin Bay was ice-free and had warmed substantially. The only sources of cold surface water were melting ice and snow near the coasts. An examination of surface temperature and salinity data tabulated by Fissel *et al.* (1980) reveals a relatively simple relationship, suggesting that, though salinity controls the density of surface waters in this region, it should be possible in late summer to use surface temperature as a tracer of surface water movements. This is confirmed by the agreement between the circulation described above and the pattern of isotherms in Figures 1 and 3 as well as the satellite imagery in Figures 6, 7, and 8.

While the average total amount of chlorophyll in the top 35 m of the water column (75 $mg \cdot m^{-2}$) in Jones Sound and Lancaster Sound was similar to that at stations in the Baffin Current, the vertical distribution was quite different. The cold, freshened surface layer in both sounds contained very little chlorophyll, but subsurface pigment maxima were found in or just below the pycnocline at most of these stations. Vertical distributions in the Baffin Current were more homogeneous.

The largest surface-layer phytoplankton standing crops were in a broad, patchy band from Jones Sound across the mouth of Lancaster Sound and south along Bylot and Baffin islands. This closely follows the position of the core of the Baffin Current, with nearly every elevated patch closely corresponding to an eddy or meander. The patch of chlorophyll encountered south of Coburg Island by both ship and aircraft was associated with eddying circulation at the convergence of two flows (Fig. 10). Similarly, the increased chlorophyll concentration detected by the ship near the outer edge of the transect east of Devon Island was in the center of a large meander which Fissel *et al.* (1982) suggest is related to local bottom topography. At the mouth of Lancaster Sound the aircraft found a large patch of chlorophyll between 5 and 10 $mg \cdot m^{-3}$ in Fissel's (1982) "central disordered zone". This area of weak and variable circulation is surrounded on three sides by strong horizontal density gradients. The fact that drogues entered this zone from the Baffin Current, where vertical stratification is weak, makes it logical to expect high primary production in this area because of the injection of well-mixed nutrient-enriched water into a zone where at least temporary stratification can occur.

The airborne data indicate a large area of generally increased but patchily distributed chlorophyll concentrations east of Bylot Island. Both patches of over 5 $mg \cdot m^{-3}$ (Figs. 4, 5) fell within a meander in the surface flow (Fig. 10). This anticyclonic meander is common during the summer (Riggs *et al.*, 1980) and is thought to be associated with a shallow seamount (Fissel *et al.*, 1982).

CONCLUSIONS

Our estimates of total phytoplankton biomass in the top 35 m of the water column in the eastern Canadian Arctic in August 1979 ranged from around 5 mg chlorophyll$\cdot m^{-2}$ in open Baffin Bay to nearly 200 mg chlorophyll$\cdot m^{-2}$ in Jones Sound. The average (n=24) was 69 mg chlorophyll$\cdot m^{-2}$. Most values fell in the range 20 to 60 $mg \cdot m^{-2}$, which is comparable to biomass estimates for this area in 1978 (Sekerak *et al.*, 1979), and for Davis Strait (MacLaren-Marex, 1979), Resolute Bay (Welch and Kalff, 1975), and Baffin Bay (Harrison *et al.*, 1982).

It should be pointed out, however, that biomass estimates based on averages will not reflect the importance of patches of high standing crops or productivity such as those we observed, since localized high concentrations will be more available to herbivores. These patches are closely linked to the physical structure of the Baffin Current, appearing where kinetic energy is available for mixing plant nutrients into the euphotic zone of meanders and eddies in the southward flow. If these perturbations are indeed tied to local bottom topography, and are therefore relatively long-lived, then this high phytoplankton production may give rise to localized concentrations of herbivores, and in part explain the high productivity at higher trophic levels of the eastern approaches to Jones Sound and Lancaster Sound. This link between phytoplankton production and physical circulation is predicted by Margalef's (1978) conceptual model of phytoplankton, life forms, and external energy. This model also predicts the importance of the diatom contribution.

It is notable that most of the major seabird colonies in the area (McLaren, 1982) are near semi-permanent ice edges or energetic eddy zones where strong oceanographic fronts are common. Most seabirds can feed only at or near the surface, and therefore rely heavily on areas where physical or biological phenomena concentrate seabird prey there, thus reducing the energetic costs of foraging (Brown, 1980). Seabirds have excellent colour vision (D. Nettleship, Canadian Wildlife Service, pers. comm. 1980) and we speculate that they are using a "remote sensing" technique similar to ours to locate water colour changes at oceanographic discontinuities where zooplankton are often concentrated. These colour changes are easily visible to the human eye under ideal observing conditions. Our instrumental technique has the advantage of minimizing confusing effects and recording the data for later computation and analysis.

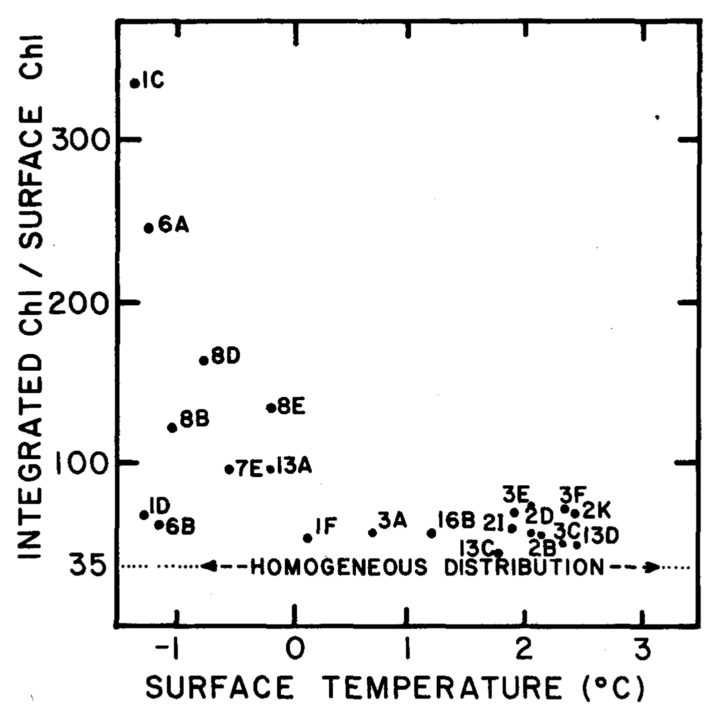

FIG. 11. Comparison of the ratio [integrated chlorophyll (0-35 m) : surface chlorophyll] with sea surface temperature. Above 0°C the surface chlorophyll concentration can be used as an index of the pigment content of the top 35 m of the water column, since the relationship between surface concentration and that in the top 35 m was relatively constant. Strong subsurface chlorophyll maxima were observed beneath cold (< 0°C) meltwater and in these areas vertical profiling becomes more important.

Our data demonstrate that aircraft can usefully supplement ships in large-scale chlorophyll surveys by extending the geographic coverage and providing more synoptic repeated data. Surface-layer surveys will give reasonably accurate representations of the total chlorophyll only where the vertical pigment distribution is homogeneous or predictable. Figure 11 shows that, for this study, the depth-integrated chlorophyll content could be estimated from surface measurements to within $\pm 30\%$ except in Jones and Lancaster Sound, where most of the phytoplankton development was taking place beneath a very cold ($<0\,^{\circ}C$) surface layer.

Platt and Herman (1983) have also considered this source of error for remotely sensed data. They conclude that it is probably no greater than the errors that arise from mapping with slowly moving surface vessels where biomass variations and water movements occur on short time scales. The large-area, rapid surveying capability of aircraft is then extremely valuable.

Satellite data provide a near-instantaneous survey of even larger areas than aircraft data. However, until 1983 when the Canada Centre for Remote Sensing began keeping a digital archive of NOAA/TIROS imagery for Canada, coverage for the eastern Arctic has been sparse because of remoteness from ground receivers and frequent cloud cover. Few thermal images are available, and no examples of water colour imagery from the Coastal Zone Colour Scanner on the NIMBUS-7 satellite have yet been processed for this area.

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