Meddelelser om Grønland

The annual cycle of phytoplankton primary production and hydrography in the Disko Bugt area, West Greenland

Ole G. Norden Andersen

Bioscience
6 · 1981

Meddelelser om Grønland

The series *Meddelelser om Grønland* started in 1879 and has since then brought results from all fields of research in Greenland. It has now been split into three separate series:

- *Bioscience*
- *Geoscience*
- *Man & Society*

The series should be registered as *Meddelelser om Grønland, Bioscience (Geoscience, Man & Society)* followed by the number of the paper. Example: *Meddr Grønland, Biosci.* 1, 1979.

The new series are issued by Kommissionen for Videnskabelige Undersøgelser i Grønland (The Commission for Scientific Research in Greenland).

Correspondence
All correspondence and manuscripts should be sent to the Secretary, Kommissionen for Videnskabelige Undersøgelser i Grønland, Øster Voldgade 10, DK-1350 Copenhagen K. Questions concerning subscription to all three series should be directed to the agent.

Agent
Nyt Nordisk Forlag – Arnold Busck A/S, Købmagergade 49, DK-1150 Copenhagen K. Tlf. +45.1.111103.

Meddelelser om Grønland, Bioscience

Meddelelser om Grønland, Bioscience invites papers which contribute significantly to the study of flora and fauna and of ecological problems pertaining to all Greenland environments. Papers primarily concerned with other areas in the Arctic or Atlantic region may be accepted, if the work actually covers Greenland or is of direct importance to the continued research in Greenland. Papers dealing with environmental problems and other borderline studies may be referred to either of the series *Bioscience, Geoscience* or *Man & Society* according to emphasis and editorial policy.

Editor
Jean Just, Zoological Museum, Universitetsparken 15, DK-2100 Copenhagen Ø. Telephone: +45.1.354111.

Instructions to authors. – See page 3 of cover.

The annual cycle of phytoplankton primary production and hydrography in the Disko Bugt area, West Greenland.

Ole G. Norden Andersen

MEDDELELSER OM GRØNLAND, BIOSCIENCE 6 · 1981

Table of contents

Received January, 1979
Accepted May, 1979
ISNN 0106-1054
ISBN 87-17-02869-8
Printed by AiO Tryk as, Odense

The annual cycle of phytoplankton primary production and hydrography in the Disko Bugt area, West Greenland.

OLE G. NORDEN ANDERSEN

Andersen, Ole G. Norden 1981. The annual cycle of phytoplankton primary production and hydrography in the Disko Bugt area, West Greenland. Meddr Grønland, Biosci. 6: 65 pp, Copenhagen 1981-08-28.*

The distribution and size of phytoplankton production and biomass in relation to physical and chemical parameters in the upper 50 m at Godhavn and in Kangikerdlak in the inner part of Disko Fjord was investigated through 2½ years (1973–75). Some data from other parts of Disko Bugt are presented.

In both locations the hydrography alternates between an unstable winter situation with isothermal (÷1.75°C) and isohaline (33.5–34.0‰) conditions throughout, and a highly stable summer situation when dilution and heating, especially of the upper 20–30 m, raise the temperature at the surface to 9.9°C and at 50 m to 3.8°C at Godhavn, and to 12°C and 3.5°C respectively in Kangikerdlak. Salinities drop correspondingly to 30.6‰ in Kangikerdlak.

The 1% depth for green light is greatly reduced beneath ice and snow. During the ice free period at Godhavn it varies from 12 m during the spring phytoplankton bloom to more than 60 m from Oct. through the winter. In Kangikerdlak the 1% depth reaches only 40 m in winter, and outflowing turbid fresh water creates 1% depths of as little as 4–5 m in June–Aug.

At Godhavn NO_3-N reaches highs of 10.05 µgat/liter and 10.15 µgat/liter at 0 and 50 m respectively in winter, whereas during the summer, depletion to less than 0.01 µgat/liter occurs in the upper 40 m and to 1.0 µgat/liter at 50 m. PO_4-P is similarly reduced from 0.8 µgat/liter and 1.1 µgat/liter to less than 0.01 µgat/liter in the upper 20 m and to 0.21 µgat/liter at 50 m. The N:P ratio drops from 13 to less than 0.01 in the upper 30 m and to 1.0 at 50 m. In Kangikerdlak depletion of NO_3-N is similar to conditions at Godhavn, whereas PO_4-P reaches a low of 0.1 µgat/liter only, while in mid summer it reaches 1.88 µgat/liter at the surface, giving an N:P ratio which is below 0.1 in the upper 5 m only.

At Godhavn primary production is about 90 gC $\cdot$ m^{-2} $\cdot$ yr^{-1} (75–104 g) with a maximum of about 5.5 gC $\cdot$ m^{-3} $\cdot$ yr^{-1} at 5–10 m, whereas in Kangikerdlak production was concentrated near the surface with about 6.0 gC $\cdot$ m^{-3} $\cdot$ yr^{-1} and a total of 35 gC $\cdot$ m^{-2} $\cdot$ yr^{-1} at most. Production at Jacobshavn off the glacier fjord is probably greater than at Godhavn, whereas at Christianshåb and Egedesminde it is definitely lower.

Phytoplankters larger than 56 µ contribute about 50% of annual and up to 90% of daily production.

Due to the great stability, production usually extends no deeper than compensation depth, and most of the chlorophyll is usually in the nutrient rich water below this depth, where it sinks, is consumed, or degrades into phaeopigment. P/B is highest where there is least chlorophyll. Light reduces production in the upper 5–10 m, and inhibition may extend to 30 m. Correlations between production, P/B, or P/B/light and nutrients reveal possible saturation values of 0.08–0.78 µgat NO_3-N/liter and 0.17–0.22 µgat PO_4-P/liter. PO_4-P seems to be the limiting nutrient in some cases, although NO_3-N is most quickly and thoroughly depleted.

Dark fixation at Godhavn is about 24 gC $\cdot$ m^{-2} $\cdot$ yr^{-1}, and at Kangikerdlak about 15 gC $\cdot$ m^{-2} $\cdot$ yr^{-1}. 55–60% of dark fixation is presumed to be biotic and 16–64% is associated with particulate matter larger than 56 µ.

Although oxygen is never at a minimum in Disko Bugt, saturation as well as absolute O_2 values and pH show profiles in the bay that clearly reflect the high degree of stratification compared to waters south of the bay.

Ole G. Norden Andersen, Zoological Museum, Copenhagen, Universitetsparken 15, DK-2100 Copenhagen Ø, Denmark.

---

*Publications from the Danish Arctic Station, No. 81.

Fig. 1: Map of the Disko Bugt area with place names and stations mentioned in the text.

Introduction

Andersen (1981) presents a description of Disko Bugt and adjacent waters including glacier and non glacier fjords with data on bathymetry, temperature, salinity, currents and water masses. The present paper deals with phytoplankton production, its size, variation and seasonal distribution, the resulting biomass, and physical and chemical factors affecting primary production. The only previous primary production experiments from the area were performed in Godhavn harbour (Petersen 1964). These are here followed by year round experiments made offshore at Godhavn and inshore in Kangikerdlak in the inner part of Disko Fjord, supplemented by a few series from other parts of the bay. (Fig. 1).

The Danish National Science Research Council has supported the preparation of this paper.

Material and methods

All previous data on O_2 ("Islands Falk" and "Dana" journals for 1925 in B. H., "Dana" journals for 1952 & 1955 at D. F. H., Martens 1929; Riis-Carstensen 1936, Jones & Folkard 1968), pH (B. H. for 1924, 1925 & 1928 (incl. Martens 1929); Riis-Carstensen 1936), NO_3

(Hagen 1936), PO_4 (Hagen 1931 "Dana" journals for 1950, 1952–55 in B. H. and for 1957 & 1971 at D. F. H.) and primary production (Petersen 1964) from the Disko Bugt area are treated along with newer measurements of temperature, salinity, pH, alkalinity (in 1973 only), total P, PO_4, NO_3, NO_2, subsurface illumination, total daily radiation (300–2500 nm), phytoplankton pigments and primary production made by the author in 1973–75, and data on wind, air temperature, cloud cover and sun shine hours at Godhavn collected by the Danish Meteorological Institute. Only temperature and salinity was measured at all stations as indicated in isopleth diagrams, whereas the other measurements were conducted in the period Mar.–Oct. On all stations measurements were made at 0, 5, 10, 15, 20, 30, 40 and 50 m, and in 1974 and 1975 temperature, salinity, and light was additionally measured at 0.5, 1, 2, 3, 4, and 7.5 m on all stations, and also at 60, 70, 80, and 90 m on the offshore stations.

In the open-water period field work was usually performed from a 34 ft fishing vessel or in a few cases from a small speed boat, whereas work through the ice was done from inside a small tent heated with kerosine burners.

Salinity and temperature was usually measured with an MC5 combination conductivity salinometer and thermobridge from Electronic Switchgear, but at times an insulating water sampler with thermometer was used and salinity was then determined by flotation. The same sampler was used in retrieving samples for determining pH, alkalinity, P, N and primary production, while water for phytoplankton pigment determinations was pumped to the surface using a lever action hand pump. pH was measured with a standard pH-meter and alkalinity was determined by back titration with HCl after addition of NaOH and total CO_2 was then found according to Harvey (1955). P and N were determined from frozen samples with an autoanalyzer at the hydrographic lab of the Danish Fisheries and Marine Investigations. Total radiation energy (300–2500 nm) was measured at Arctic Station, Godhavn with a Kipp and Zonen solarimeter and the relative subsurface intensity of green light was measured in μamp. with deck and submarine selenium cell photometers using a Chance-Pilkinton O Gr 1 green filter.

In order to measure the illumination beneath the ice out of reach of the shade from the tent, the submarine photometer was lowered with the aid of a block fastened to the middle of a rope suspended beneath the ice between the working hole inside the tent and a hole chiseled about 5 m from the tent. The ice chisel consisting of a 25 cm blade and socket fastened to a $1^3/_4$ m wooden handle was used in pulling the rope from one hole to the other. The rope was fastened to the blade, and gripped by the blade, the chisel was thrust handle first through the outside hole at a 45° angle in the direction of the hole under the tent. The chisel was hereby directed handle first up through the hole at which it was aimed and would – if the blade was not too heavy – end up there with the tip of the handle projecting above the surface.

From the solarimeter readings, from heliograph recordings, from data on cloud cover noted every 3 hours, and from sun altitudes the direct and the sky radiation reaching the sea surface every hour has been calculated for the days, when submarine light measurements were performed. Then, using the values for global radiation under clear and cloudy conditions given by Sauberer (1962), the dependence of sky radiation on cloud cover and sun altitude from Sauberer & Ruttner (1941) and Sauberer & Dirmhirn (1954) and the spectral distribution given by Sauberer & Ruttner (1941) and Strickland (1958), an absolute value for direct and sky radiation (500–550 nm) was obtained for every hour. Finally the total daily radiation (500–550 nm) at 0–50 m was obtained from reflection values for direct and sky radiation (Sauberer & Ruttner 1941) and from the extinction coefficients derived from the sub-marine measurements of green light according to Vollenweider (1955) corrected for angular distribution according to Johnson & Liljequist (1938). The enhancing effect upon surface transmittance of light exerted by waves at the low solar altitudes prevailing at this latitude has been omitted in the calculations, since it amounts to a few percent only (Cox & Munk 1956, Andersen 1977a).

Primary production was measured in situ using the standard ^{14}C technique with 2 light and 1 dark bottle of 100 ml each, incubation with 1 ml ampoules of 4 μCi, filtration through 0.2 μ Whatman membrane filters, air drying and final GM-counting after subjection to HCl fumes at the ^{14}C Agency in Denmark.

Chlorophylls were measured by filtering 2–5 liters of sea water through 0.4 μ GFC Millepore glass filters with 3 drops of 1% $MgCO_3$ suspension added, extraction in 90% acetone in distilled water for 24 hours at ÷18°C following a maceration of the filter, and finally centrifugation and measuring of supernatant at 630, 645, 663 and 775 nm followed by an addition of HCl and remeasuring for determining phaeopigments according to Carlberg (1972).

Hydrography of the upper 50–90 m off Godhavn

The isopleth diagrams for temperature and salinity at Godhavn (Figs 2–7) give an immediate impression of great variability. The general scheme is as follows: A winter condition of uniform salinities and low temperatures in the upper about 80 m is followed not only by solar heating but also by large amounts of fresh water from land, glaciers and melting sea ice and ice bergs gradually blotting out the winter-cooled layer and creating a surface layer of increasing thickness with

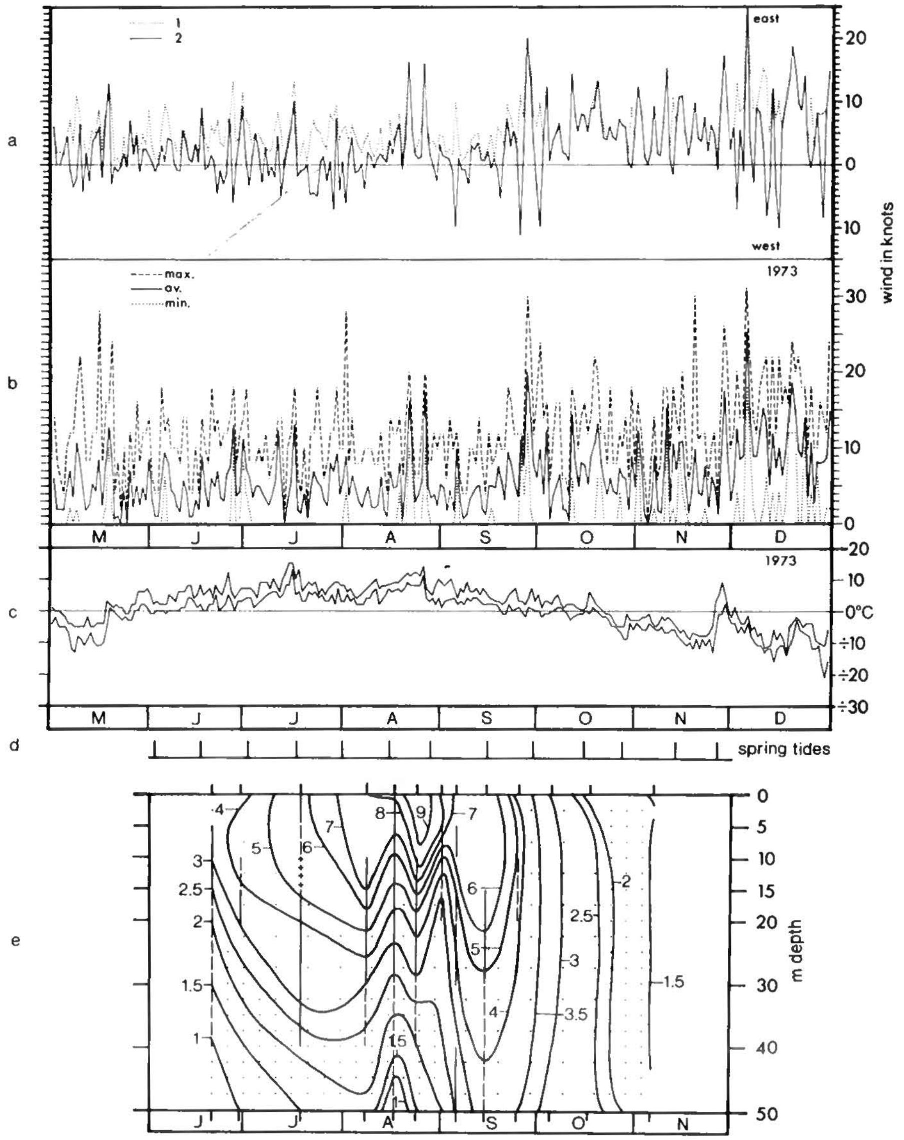


Fig. 2: Godhavn 1973. a: (1) Daily average wind speed (knots), (2) Daily vectorial average wind speed (knots) and direction from E (0–179°) and from W (180–359°). b: Daily maximum, minimum and average wind speed (knots) recorded every 3 hours. c: Daily maximum and minimum air temperatures. d: Spring tides (from tables issued by the Danish Farvandsdirektoratet). e: Isopleth diagram showing temperatures (°C) recorded on dates marked below and at depths indicated at the right. Changes in temperature with depth – positive or negative thermoclines – are indicated as follows: Full vertical ≥ ÷1° per 10 m, dashed vertical ≥ ÷1° per 25 m, barred vertical ≥ +1° per 10 m, and crosses ≥ +1° per 25 m. a–c recorded at the Godhavn telegraph station.

warmer less saline water separated by combined halo- and thermoclines from cooler and more saline water found below. Deeper water is also active in forcing the winter-cooled water towards the surface, where it is swept out of Disko Bugt. In the fall the reduction in solar heating and in the amounts af fresh water being added to the surface layers of the bay as well as an increase in windiness extends cooling and mixing to greater and greater depth gradually restoring winter conditions.

Salinity – with some remarks on wind and tides

Salinity off Godhavn is influenced by fresh water from land, sea ice and ice bergs, by wind mixing and by currents (tides).

A preliminary freshening of the surface layers occurs in May, when the sea ice disappears for good, and the greater part of the snow and ice on land melts away, but it is not until about mid June or early July that an extensive freshening sets in. The lowest surface salinities

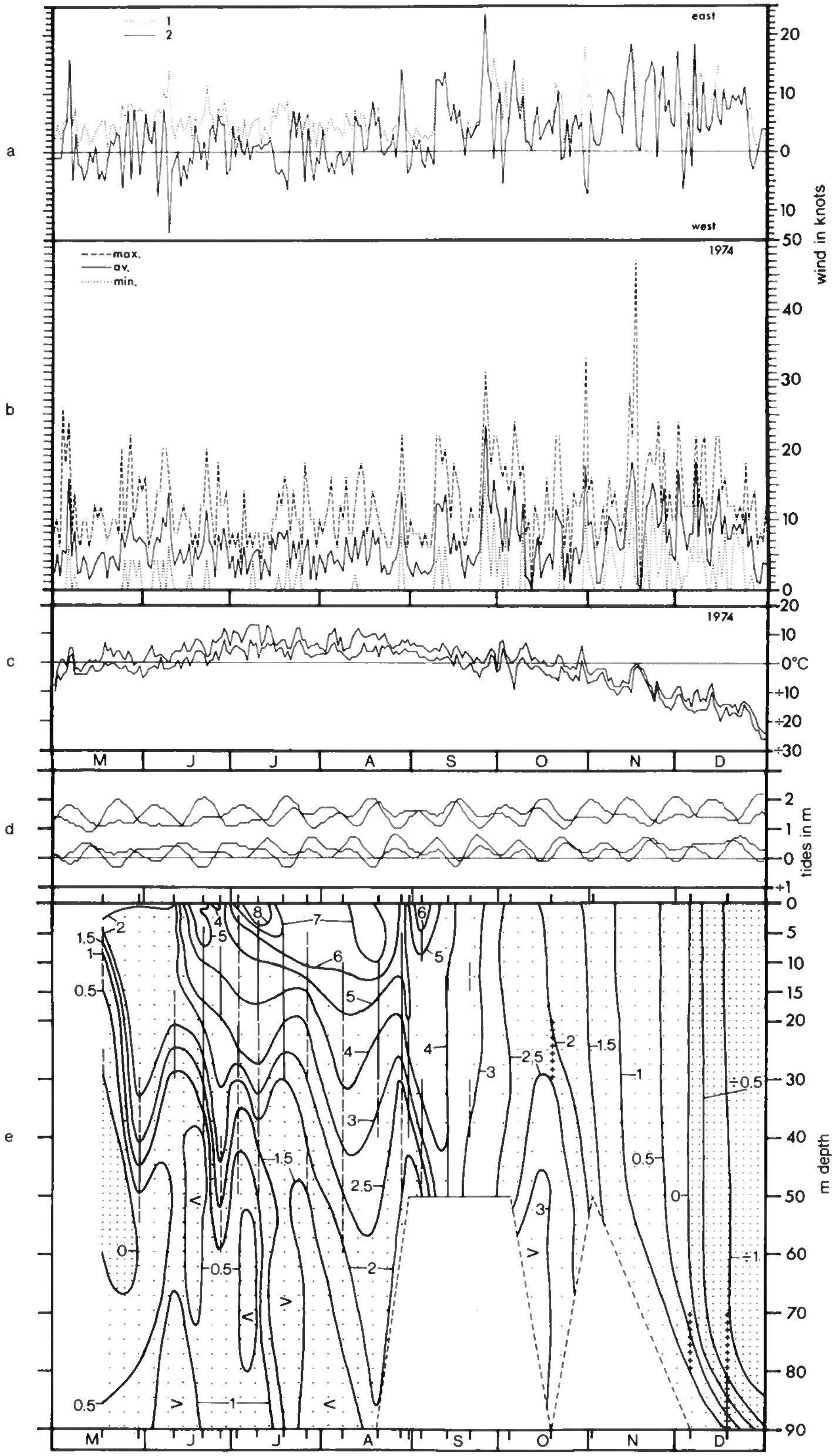
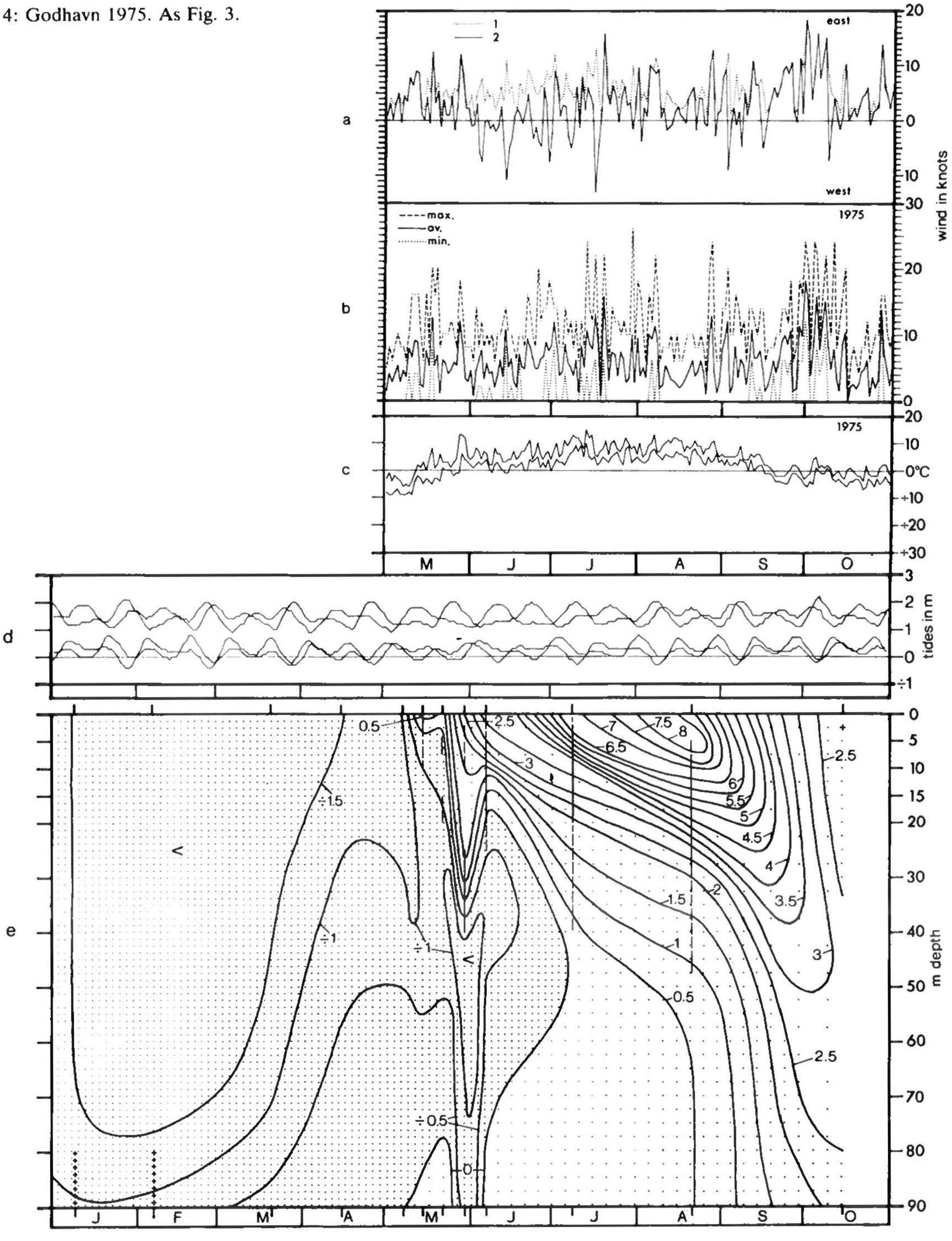


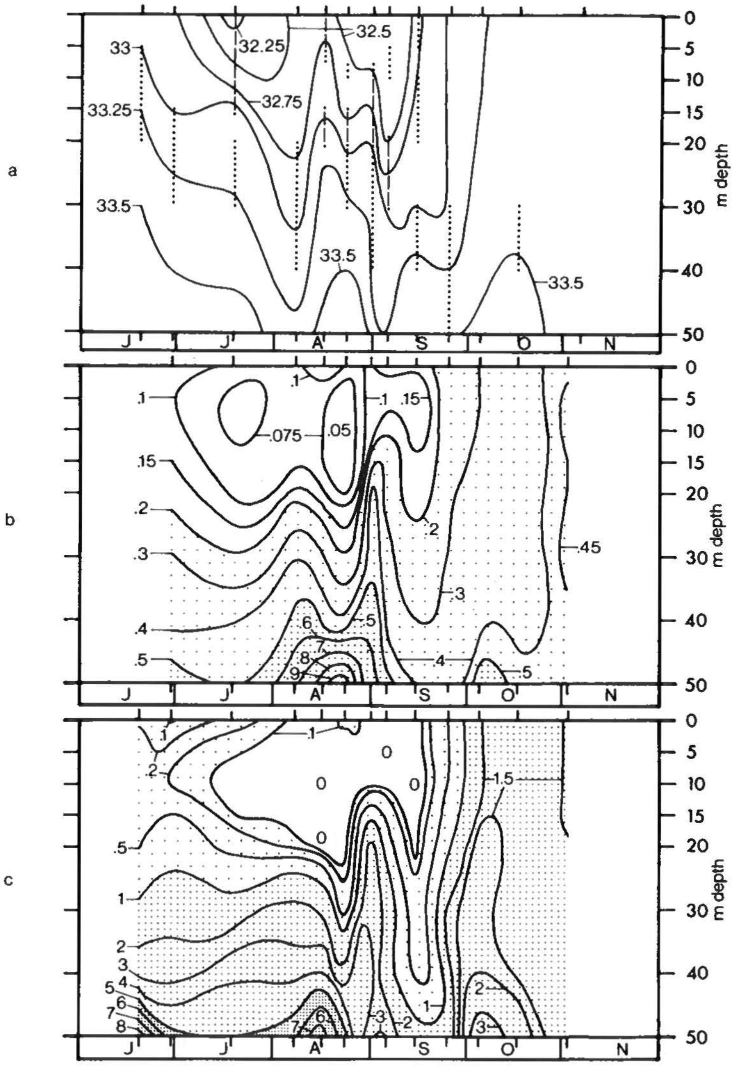
Fig. 3: Godhavn 1974. a–e as in Fig. 2, exept that in the 90 m series, temperatures were also measured at 0.5, 1, 2, 3, 4, and 7.5 m.

Fig. 4: Godhavn 1975. As Fig. 3.



exist in July and Aug., whereas the distinct freshened surface layer bounded below by a steep halocline reaches its greatest magnitude in Sept. After this the drop in solar radiation, and in air temperature – largely to below freezing – reduces the supply of fresh water being added to the surface layer, allowing surface cooling and mixing aided by the more frequent and stronger fall winds to create uniform salinities – slightly lower than found in the spring – in a surface layer of increasing thickness.

Fig. 5: Godhavn 1973. a: Isopleth diagram of salinity (‰). Changes in salinity with depth – haloclines – are indicated as follows: Full vertical≥ + 1‰ per 10 m, dashed vertical ≥ + 1‰ per 25 m, and dotted vertical ≥ +1‰ per 50 m. b: Isopleth diagram of PO_4-P in µgat/liter. c: Isopleth diagram of NO_3-N in µgat/liter. Depths are indicated at the right and dates marked below.



The winds vary tremendously from day to day and even from hour to hour with relation to both speed and direction (Figs 2–4). Least variations occur in the summer months from May to early Sept., where the average monthly wind speed is quite uniform from year to year and from month to month (Fig. 11G), while from Oct. to Dec. the day to day variations are much greater and the monthly averages increase. As shown in Fig. 11D the balance between E and W winds is best from May to July, after which the stronger E winds become increasingly dominant supporting the surface current flowing past Godhavn out of the bay. During the winter these strong winds, foehns, may from time to time break up the ice in the entire bay, especially if they occur during spring tides, which quite often is the case. In late May and early June, when the ice has gone, strong winds are able to mix the upper 30 m of sea water, but later in the summer the effect of the often quite strong winds goes no deeper than about 10 m, due to the stabilizing of the upper layers, primarily caused by lowered salinity. It is not until late Sept., when the fall storms set in, that both surface cooling and a reduction in the freshening of surface layers make a thorough mixing process possible. Hydrographic observations are too few and too widely spaced to allow any correlation between daily changes in wind velocity and direction and salinities. An attempt to do this is also impeded by the fact that winds measured at Godhavn often are local in character, and may be quite different from conditions prevailing a few km off shore. There are implications in the wind and salinity data, however, showing that moderately strong E winds (less than 10 knots) under the most stable summer conditions create the lowest salinities in a shallow surface layer by aiding the outflow past Godhavn. Stronger

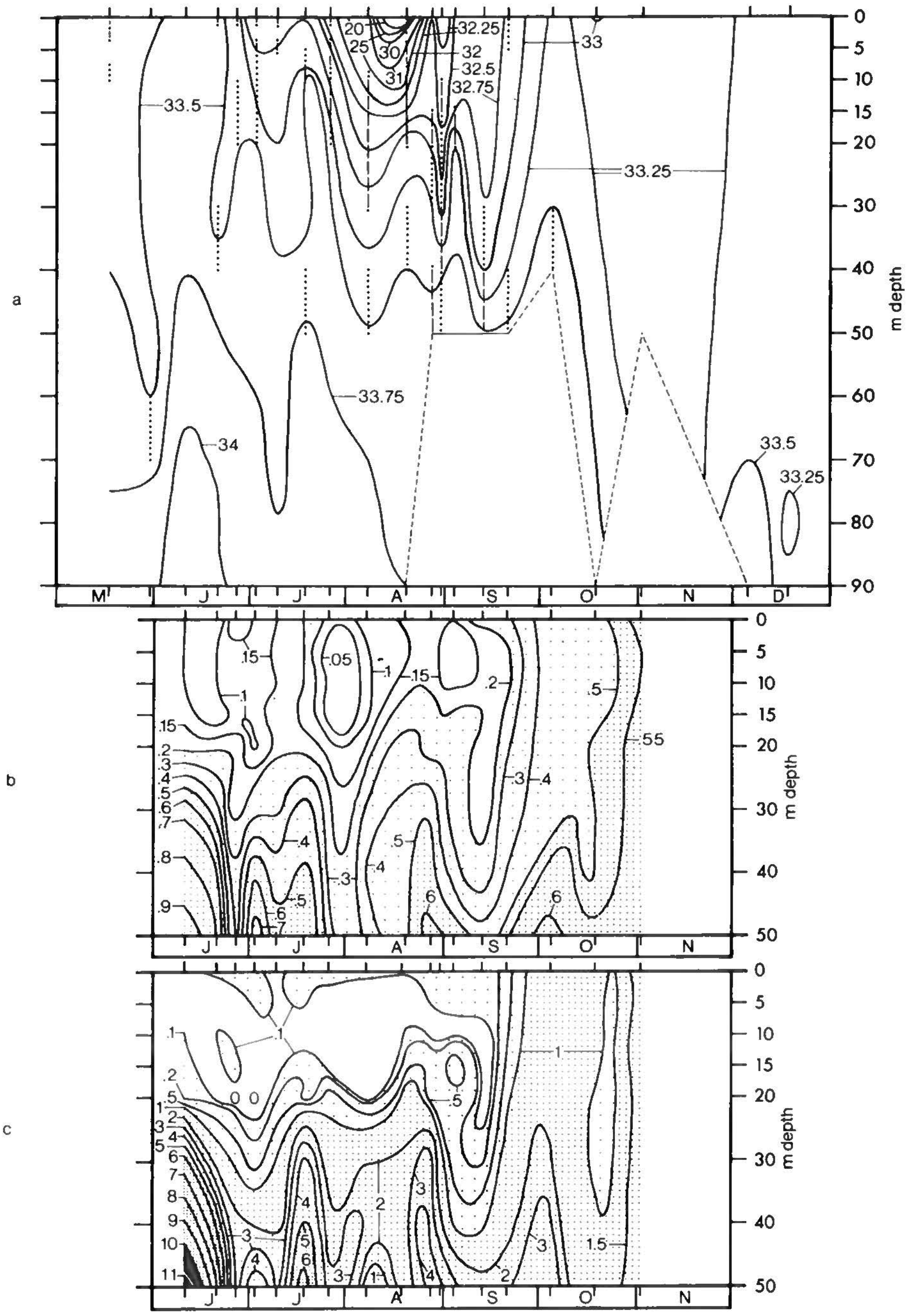


Fig. 6: Godhavn 1974. As Fig. 5, except that the 90 m series include records at 0.5, 1, 2, 3, 4, and 7.5 m.

winds from the E and especially W winds are most active in mixing the surface layers during the summer.

The variations in salinities below the surface layers existing during the summer reflect irregular changes in a balance between outflowing freshened and warmed surface water and cooler well mixed more saline water from the West Greenland Current intruding beneath this surface layer, and to some extent upwelling in the area. There seems to be no connection between these variations and the prevailing winds, however, which may be because the winds are often local in nature. An exception is perhaps found in Sept.-Oct. 1974, when persistent E winds are concurrent with an upwelling of saline water (Figs 3a & 6a). It can be seen by direct observation that tidal currents are active in mixing the upper strata of water off Godhavn, but no clear re-

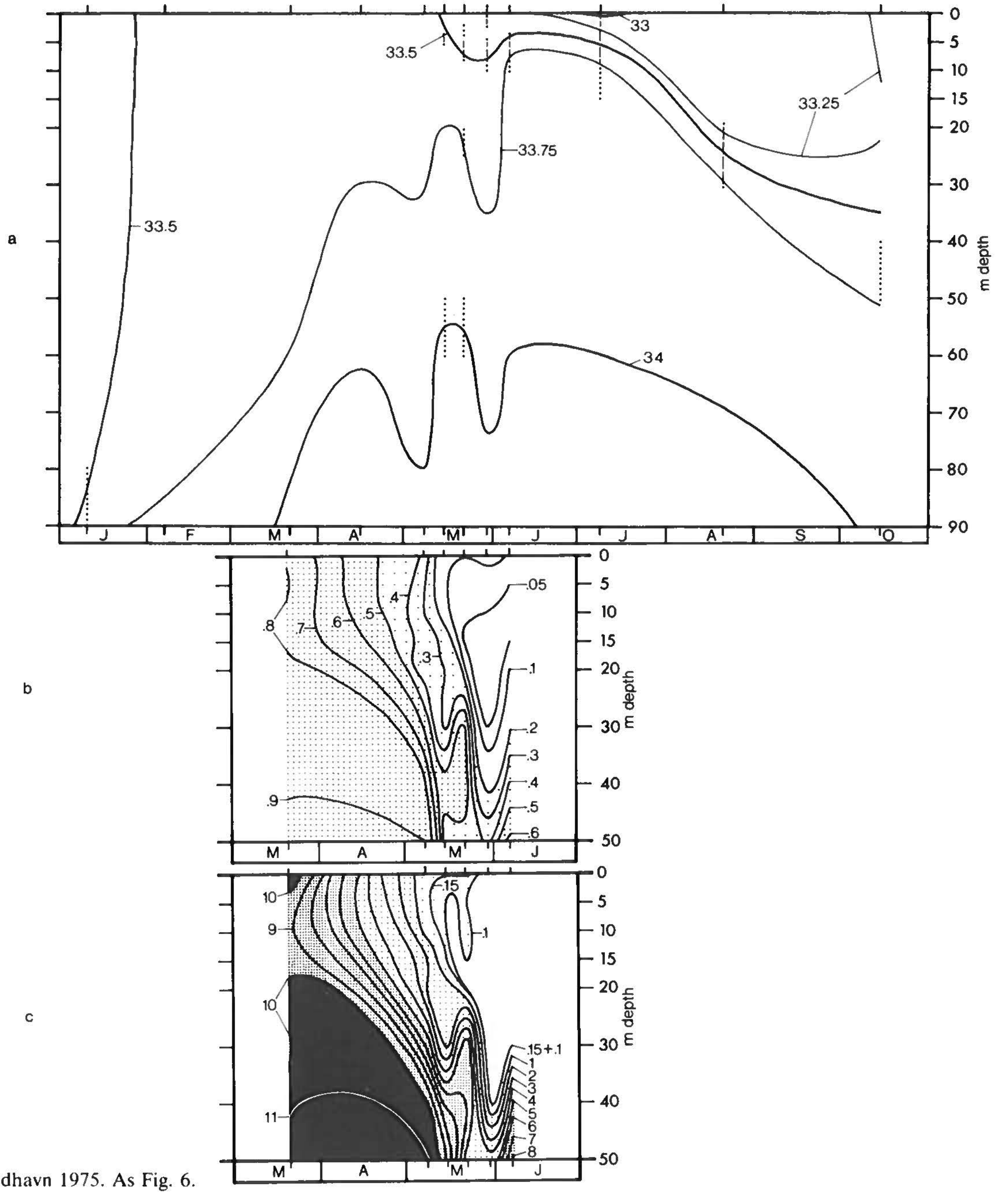


Fig. 7: Godhavn 1975. As Fig. 6.

lationship exists between the pattern of spring and neap tides and the variations in salinity (d in Figs 2–4 & a in Figs 5–7). In Disko Fjord, however, where hydrographic conditions are less varied, upwelling of saline water seems to be associated with high spring tides, and since such upwellings at the same time are apparent off Godhavn, the tidal cycle is presumed to have a precise – though obscured – effect upon the hydrographic balance here also.

Temperature – with some remarks on wind and tides

Surface temperature is a function of solar radiation, air temperature, the cooling or heating effect of run off from land and of the cooling effect of melting sea ice and ice bergs which, as shown earlier, is especially noticeable off Jakobshavn Isfjord. The depth to which heating extends depends upon the transparency of the water and the degree of vertical mixing by wind action,

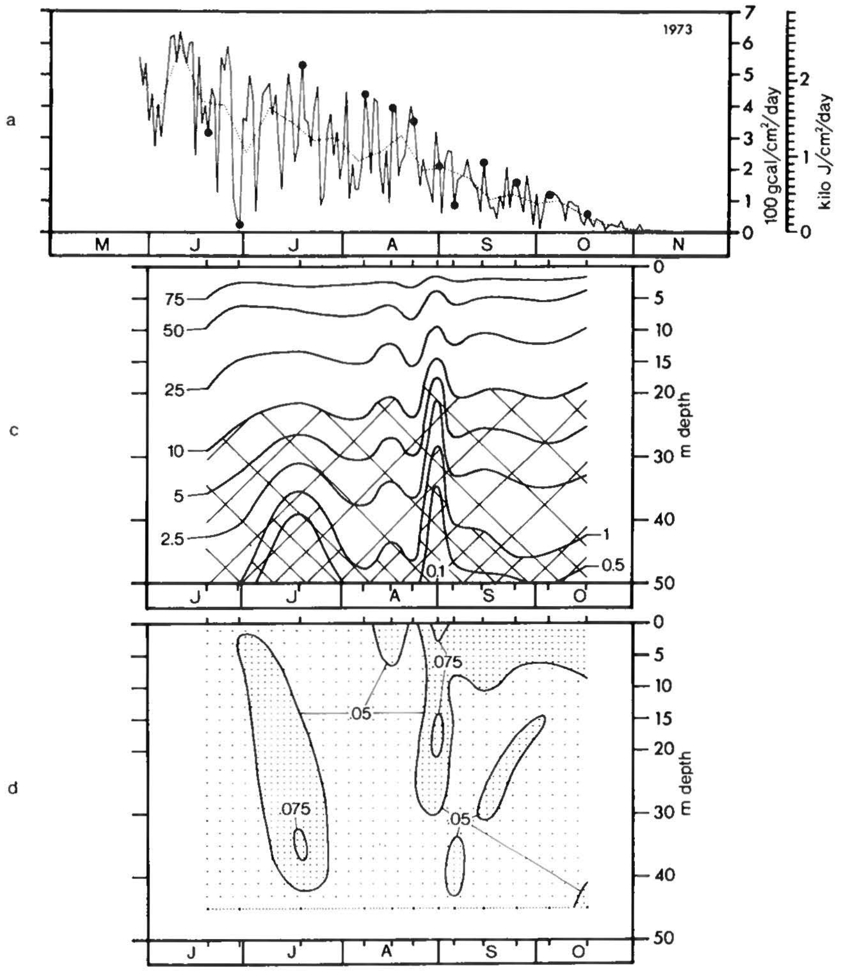


Fig. 8: Godhavn 1973. a: Daily total irradiance (300–2500 nm) (full line), and weekly means (dotted line). Dates, when submarine measurements were made, are marked. b: (see Figs 9 & 10) Isopleth diagram of total daily irradiance in gcal/cm^2/day (500–550 nm), derived as described in the text. c: Isopleth diagram of percentages of total daily surface transmission (500–550 nm). d: Isopleth diagram of extinction coefficients (^{10}log basis). Measurements made at depths indicated at the right and on dates marked below.

currents and swell, again dependent upon the stabilizing action of lowered salinity and raised temperatures in the upper strata.

Because of the rapid exchange of water masses off Godhavn it is not possible to make a heat budget study of the area, but only to discuss the effect of some of the factors involved.

Due to clouds and fog occurring later during the summer, May was in 1974 and 1975 the month with the greatest influx of solar radiation closely followed by June and July (Fig. 11E). The highest average air temperatures were found later in the year in July and Aug. (Fig. 11F), at which time the highest surface temperatures were also reached, in part due to the low surface salinity and great stability prevailing at that time.

As pointed out by Petersen (1964) the highest temperature reached at a given depth occurs later in the year at increasing depths. At Godhavn, as in most of the bay, the heating from the surface reaches its greatest depth in Sept. – early Oct., when, as shown in Figs 2–4, surface cooling is well under way. This delay in the occurrence of the temperature maximum with depth is due to the stratification, which comes to exist in the surface-near water, when the ice breaks up and begins to melt in May and especially when the effluents from Jakobshavn Isfjord and the melting ice bergs reach Godhavn in June – July. The extent of vertical mixing and heat transport from the surface down thus closely follows the freshening process, which can be seen by comparing the isopleths for salinity with those for temperature during spring and summer (Figs 2–4 & 5–7). In the fall, however, when surface cooling sets in, the stratification according to salinity is active in insulating the deeper warmed water against cooling, whereby the effect of delayed maxima with depth arises. The consequence of this is not only that summer-warmed subsurface water can be found later in the year, than would be the case under oceanic conditions with very small variations in salinity, but also that higher temperatures are attained at greater depth, while surface cooling is under way. Were it not for the cooling effect of the ice bergs, temperatures would be even higher.

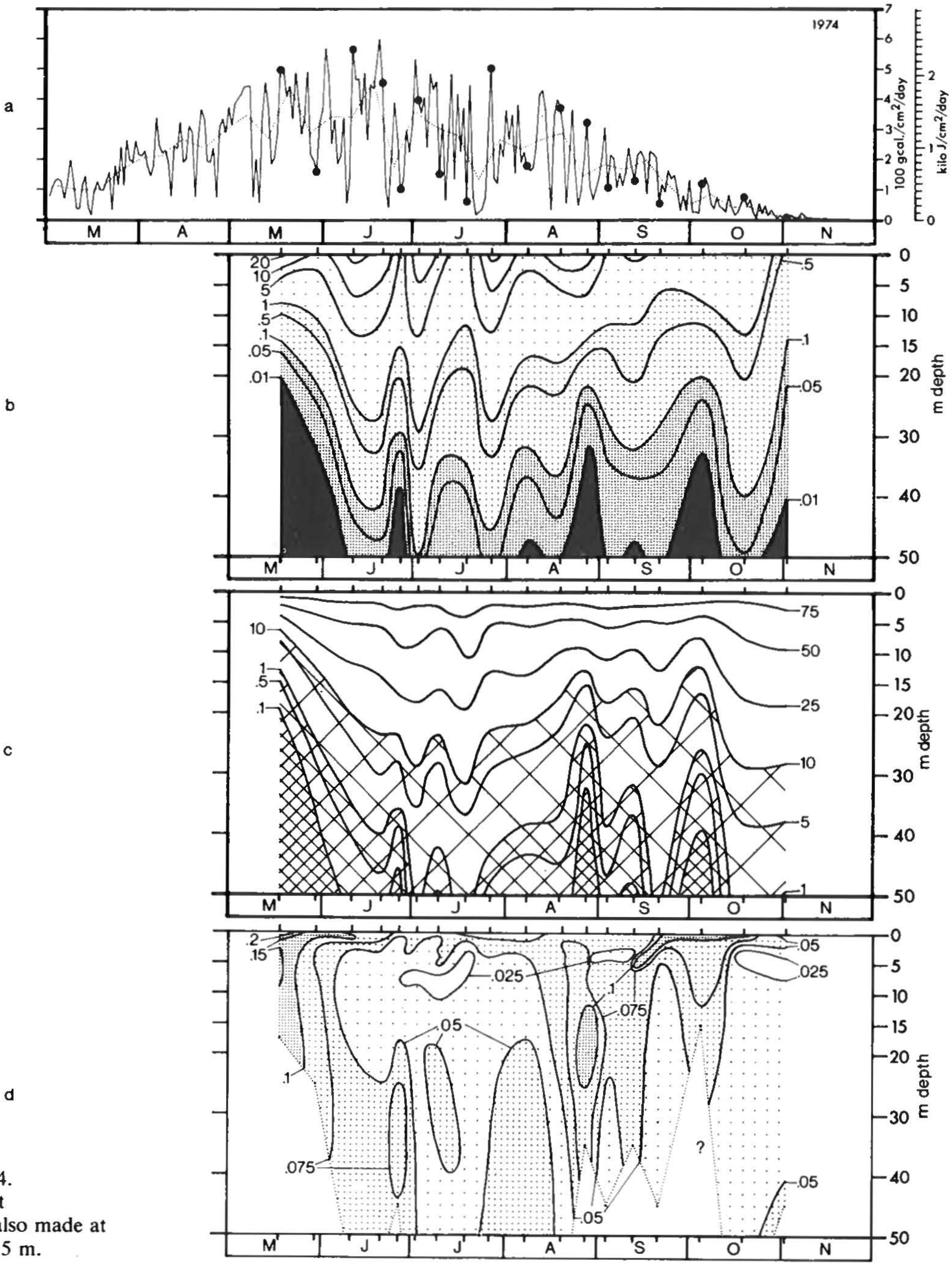


Fig. 9: Godhavn 1974.
As Fig. 8, except that measurements were also made at 0.5, 1, 2, 3, 4, and 7.5 m.

As mentioned above, there are great variations in the speed and direction of winds off Godhavn. E winds are generally strongest and warmest and foehns come from that direction, often raising the air temperature considerably within a few hours, as in late Nov. 1973 (Fig. 2). NE winds, however, can be very cold, as in late Sept. 1975 (Fig. 4). While the curves for the monthly means of air temperature (Fig. 11F) follow the curves for radiant energy (Fig. 11E) quite well, with a lag of about a month to a month and a half, the day to day variations are primarily caused by the changing wind directions. The series of temperature measurements from off Godhavn, however, are generally too widely spaced to reveal any relationship between the daily energy influx and air temperature and the temperature of the water. Vertical mixing and heat transport from the surface down, in the warmest period, is enhanced by the high degree of stability. But a combination of high energy influx, high air temperatures and strong and warm E winds may create very high temperatures, even well below the surface. On the first calm day following a period with such favourable conditions in late Aug. 1973 the highest temperatures measured from 1973 to 1975 were found in the upper 10 m, below which a major discontinuity layer stretched to 30 m (Figs 2 & 8).

In late winter and early spring it is evident that warming of the surface layers also occurs from beneath by water from the West Greenland Current. During the summer, this intruding water, reaching the area either directly from the S or from E of Kronprinsen Ejland, at first constitutes an extensive warm and comparatively saline layer separated from the surface-heated water by a remnant of winter-cooled water with minimum temperatures at about 50 m in late May to early July descending to below 100 m in Aug. By Sept., when surface cooling sets in, there is a continuous negative thermocline from the surface down to 200 m or more (cf. Andersen 1981).

Despite the swift tidal currents occurring off Godhavn and the effect of the tides upon the movements of the ice bergs passing Godhavn, the temperature variations do not reflect the pattern of spring and neap tides (Figs 2–4), although there well may be a relationship.

Illumination

At Godhavn the sun stays below the horizon for 43 days (2 Dec. – 13 Jan.) each year, and during the period with midnight sun, when the sun is hidden behind the high mountains of Disko for at least 4 hours each night, the greatest midnight and noon declinations are 2.7° and 44.2° respectively. The total yearly irradiance, according to solarimeter readings (300–2500 nm) from June 1973 to Dec. 1975 is about 225–230 kJ/cm². May and/or June were the months with the greatest energy input (Fig. 11E). The highest daily total is about 2.65 kJ/cm², the variation from day to day can be as much as 1.8 kJ/cm², and the monthly amplitude reaches 2.55 kJ/cm²/day. Mid summer values can be as low as 0.1 kJ/cm²/day due to clouds, precipitation and fog.

The primary factor limiting the penetration of light into the sea during part of the year is the sea ice, and especially its cover of snow (Andersen 1977b), through which only a few percent (1–3.5%) pass in Mar. and Apr. (Figs 12 & 46). The low declination of the sun, especially when it is less than 30°, causes a large part of the light to be reflected from the sea surface (Jerlov 1968, Andersen 1977a). It is, however, the daily surface irradiance which is the primary factor determining the light conditions in the upper 50 m in most of the period without ice cover.

Isopleth diagrams of daily subsurface irradiance (b in Figs 9 & 10), and of relative values (c in Figs 8–10) do not depict the true complexity caused by great day to day variations in amounts and types (direct solar and sky) of radiation.

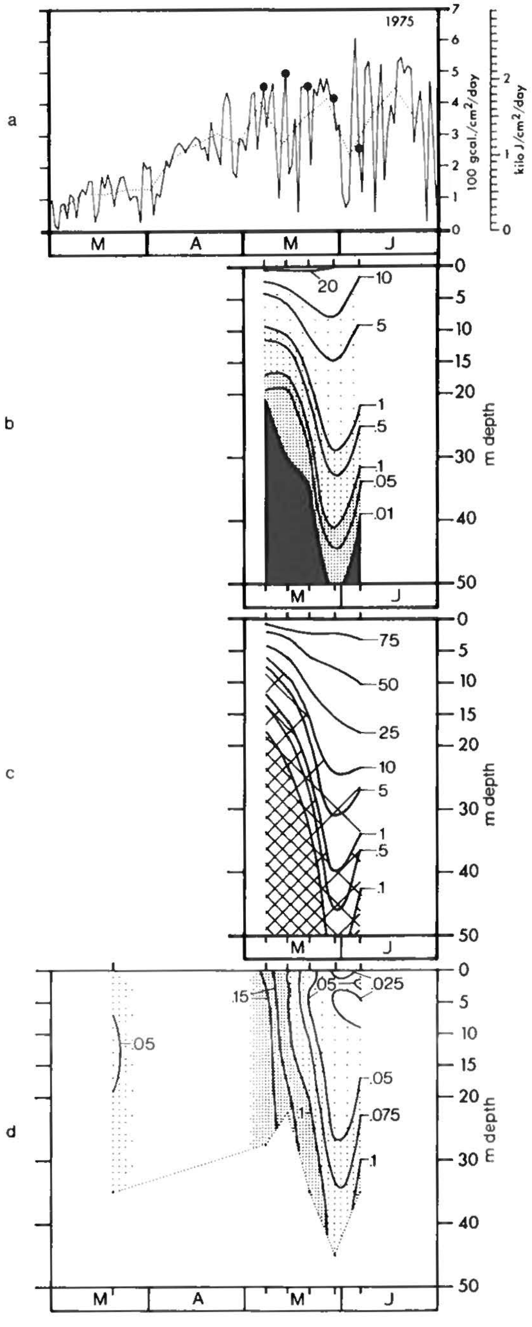


Fig. 10: Godhavn 1975. As Fig. 9.

The depth of penetration of surface transmitted light depends on declination of the sun, on wave length and on attenuation caused by turbidity (plankton, detritus) and dissolved matter. Attenuation varies considerably through the year, as shown in Figs 12 & 46. Extinction coefficients are of increasing importance for in situ light conditions with increasing depth (c in Figs 8–10).

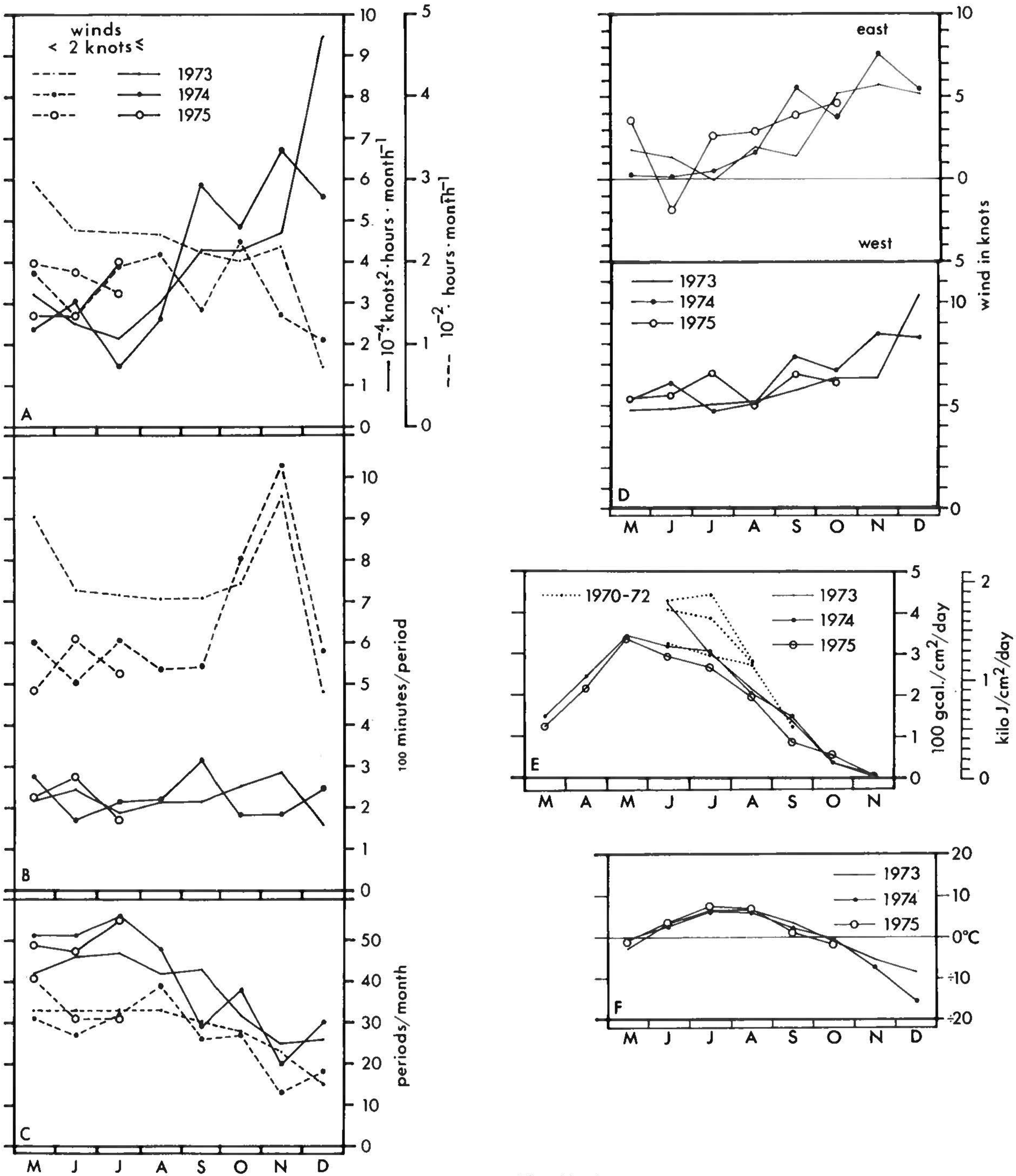


Fig. 11: Godhavn 1973–75. A: Monthly totals of turbulent energy exerpted by winds ≥ 2 knots expressed as knots² · hours · 10^{-4}, and monthly duration of winds < 2 knots in hours · 10^{-2}. B: Monthly means of duration of periods with winds ≥ 2 knots and winds < 2 knots. C: number of periods per month with winds ≥ 2 knots, and winds < 2 knots. D: Upper: Monthly means of daily mean vectorial wind speed in knots and direction (E = 0–179°, W = 180–359°). Lower: Monthly means of daily mean wind speed in knots (recorded every 3 hours). E: Monthly means of daily total irradiance (300–2500 nm) – incl. 1970–72. F: Monthly means of daily air temperature.

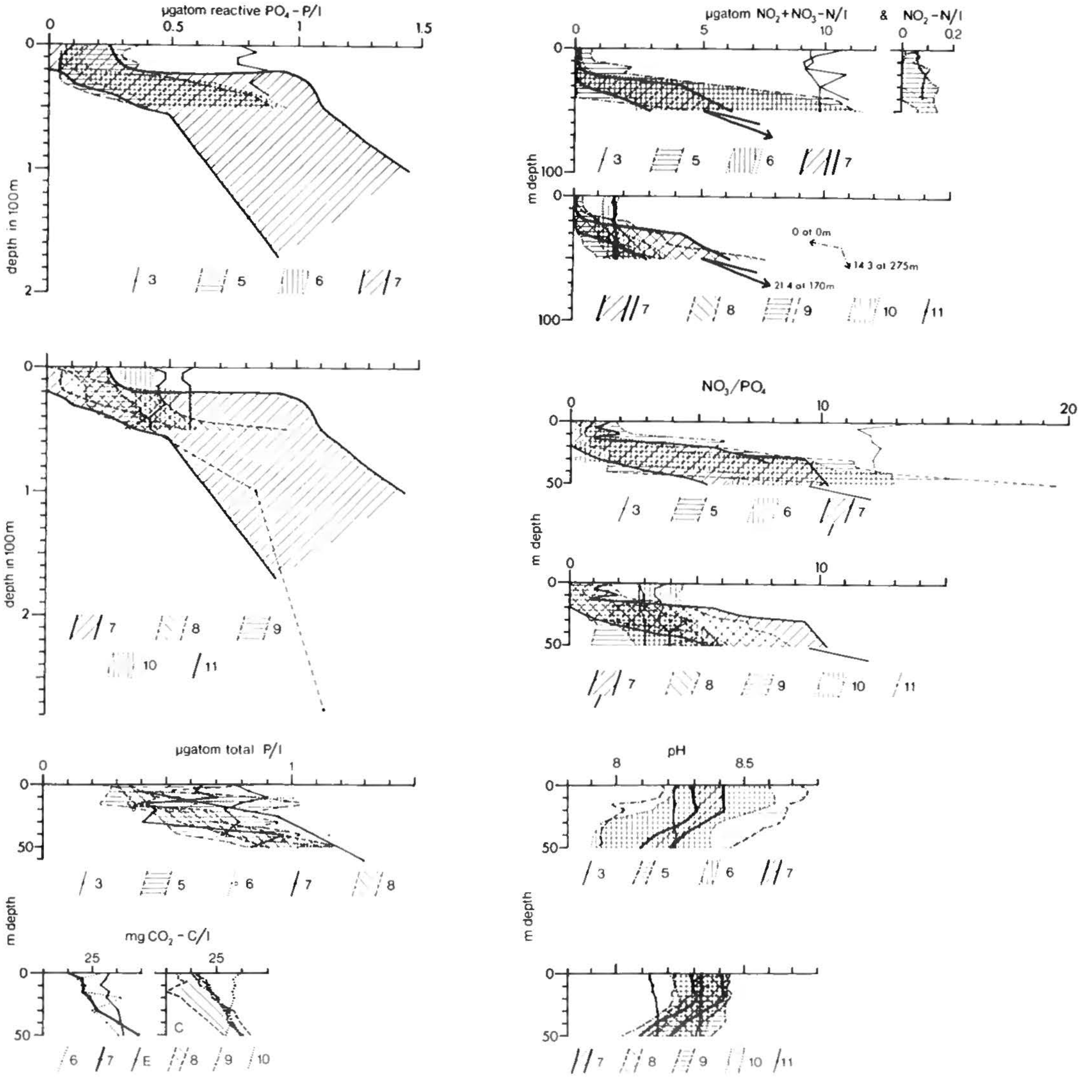
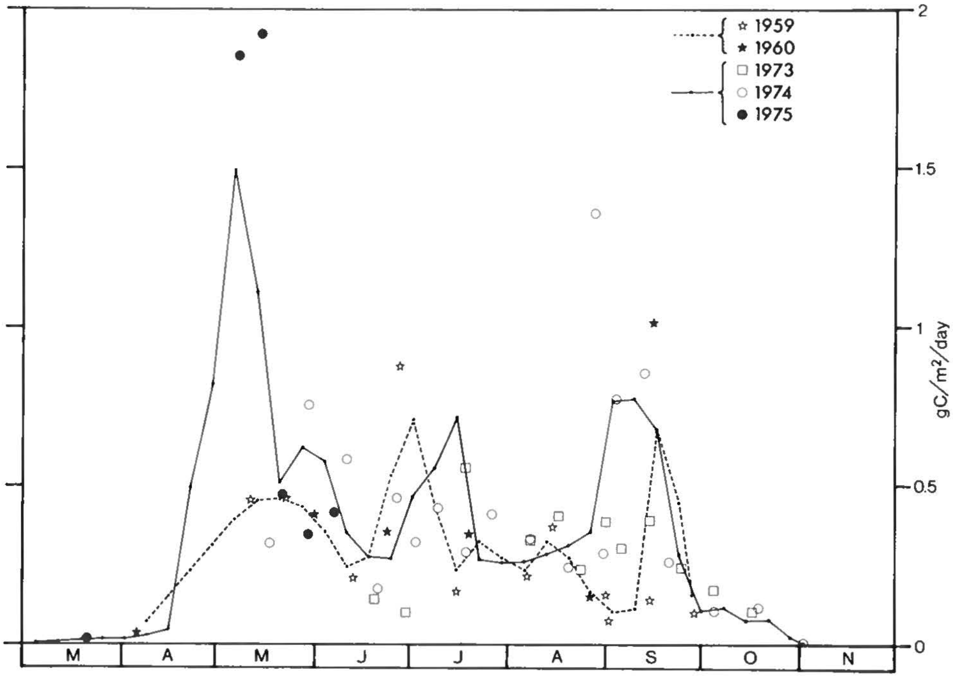


Fig. 14: Godhavn. Nutrients, pH, and CO_2–C. The data on each element are shown for each month (numbered 1 to 12) either as single series (when only one or two series exist from the month in question), or by hatched areas bounded by curves representing the highest and lowest values found at each depth. NO_3–N includes NO_2–N.

element	month	J	F	M	A	M	J	J	A	S	O	N	D
	no. in Fig.	1	2	3	4	5	6	7	8	9	10	11	12
PO_4-P	no. of ser.			2		4	5	11	7	7	4	2	
	dates			16+20		7–29	6–29	2–29	7–31	3–24	4–18	1+2	
total P	no of ser.			1		7	4	2	3				
	dates			20		7–29	6–29	8–18	7–23				
NO_3–N	no. of ser.			2		4	6	6	7	6	4	2	
	dates			16+20		7–29	6–29	2–26	7–31	3–24	4–18	1+2	
NO_2-N	no. of ser.			1		4	1						
	dates			20		7–29	6						
NO_3-N/	no. of ser.			2		4	5	6	7	6	4	2	
PO_4-P	dates			16+20		7–29	6–29	2–26	7–31	3–24	4–18	1+2	
pH	no. of ser.			1		6	6	5	6	6	4	2	
	dates			20		7–29	6–29	6–26	7–31	3–20	4–18	1+2	
	no. of ser.						1	1	3	2	2		
CO_2	dates						29	18	7–31	5–14	4–16		
	E = 26 July at Egedesminde												

Fig. 15: Godhavn 1959–60 & 1973–75. Primary production (gC/m^2/day). Plots for each experiment and curves for weekly means derived directly from experiments in 1959–60 and as described in the text for 1973–75 (as in Fig. 16).



low that they have not been recorded, except in the cases shown in Fig. 14.

pH

While under the unstable conditions found off Godhavn from Oct. to Apr. pH values vary very little in the upper 50 m, as shown in Fig. 14, decreasing pH values down through the combined thermo- and haloclines are characteristic of the summer months. The highest pH values are attained during the spring bloom in the plankton, at or just above the depth, where primary production is greatest. While the surface and surface-near values generally are higher than the winter pH values, the drop down through the discontinuity layer often brings pH values well below the winter values. The lowest pH values found off Godhavn existed below the euphotic zone during the spring bloom, where large amounts of decomposing algae were found.

CO_2-C

CO_2-C was measured in 1973 only.

The CO_2-C profiles primarily follow the salinity profiles, except when pH is exceptionally high or low which, as opposed to conditions in Kangikerdlak, does not occur off Godhavn (Fig. 14) (see also Fig. 17b).

Primary production by phytoplankton in the upper 50 m off Godhavn

Annual and seasonal rates

The only previous production measurements from Disko Bugt (Petersen 1964) were performed at Hvidfiskeøerne in the entrance to the harbour at Godhavn in 1959–60. The results gave a measure for annual production amounting to 52.2 g C/m^2 (Fig. 15). Experiments performed off Godhavn in 1973–75 yielded results showing a greater annual production of 91.6 g C/m^2 (Fig. 15). The data from the 3 years – shown as bars in Fig. 16 – give, if calculations are done by direct interpolation, as has been done with the data from 1959–60, the results shown in brackets in Table 3.

If production on the days, when experiments were not performed, however, is found by multiplying the daily insolation by interpolations between the production efficiencies expressed as produced carbon per unit of incident energy of 300–2500 nm calculated for the two neighbouring production experiments, the size of the annual production is altered by as much as about ± 21.5%, as shown in Table 3.

The difference between the results from 1959–60 and those from 1973–75 – the latter being about 75% greater than the former – is not so surprising, when one compares overlapping periods from experiments performed in the years 1973–75. Production from 19 June to 1 Nov. 1974 was about 80% greater than that meas-

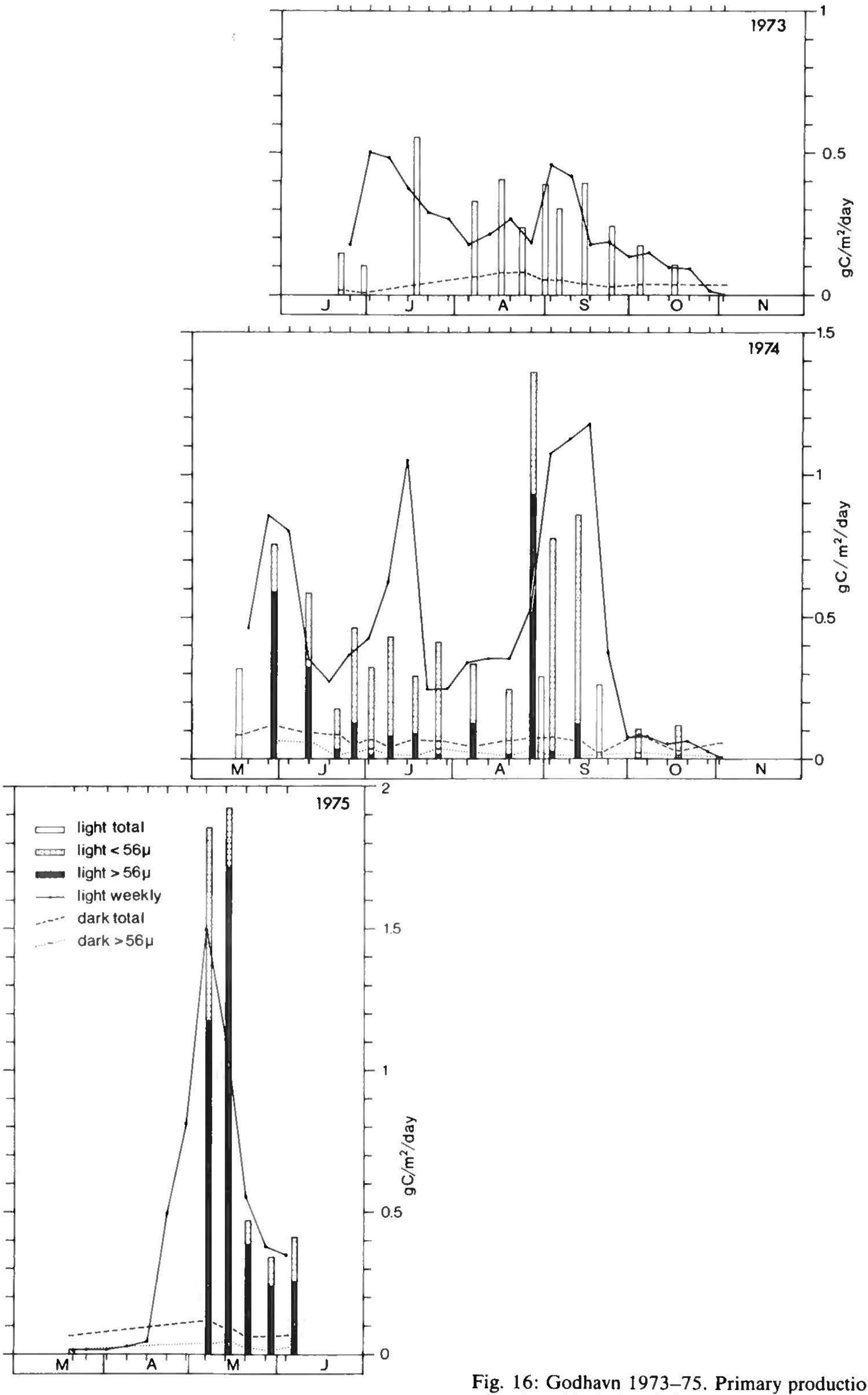


Fig. 16: Godhavn 1973–75. Primary production (bars) and dark fixation of carbon (dashed and dotted curves) in the upper 50 m for each experiment (gC/m²/day), and full curves for weekly means found as described in the text. Fractioning in nannoplankton (0.2–56 µ) and microplankton (> 56 µ). Light = light experiment ÷ dark experiment.

Table 3: Primary production at Godhavn in the productive period Mar. – Oct. Subdivision into periods covered by experiments in each of the 3 years. a: The uncorrected production for each year is shown in brackets followed by the % correction according to illumination as described in the text, and the resulting corrected production. b: Corrected production of non-overlapping and overlapping periods, the former plus means of the latter are listed at the right and summed below. Corrected sums of periods giving the lowest and the highest annual production are shown below.

months	March April May	May June	June	June July August September October	mg C/m^2 corrected means
periods	16	17 6	7 18	19	
a 1973				(37185 mg C/m^2) ÷ 9% = 33840 mg C/m^2	
a 1974		(67845 mg C/m^2) + 17.8% = 79924 mg C/m^2			
a 1975	(47490 mg C/m^2) ÷ 21.6% = 37255 mg C/m^2				
b 1973				33840 mg C/m^2	47514
b 1974				61189 mg C/m^2	
b 1974			3898 mg C/m^2		3898
b 1974		14847 mg C/m^2			11945
b 1975		9053 mg C/m^2			
b 1975	28202 mg C/m^2				28202
sum of corrected means for 1973 - 75					91559
corrected sum of	1975	1975	1974	1973	74993
corrected sum of	1975	1974	1974	1974	104238

ured for the corresponding period in 1973, and production from 17 May to 6 June 1974 was about 65% greater than in 1975.

These last comparisons, however, are not fully comparable to the others, since they do not cover the entire productive season and therefore show greater variation than if entire productive seasons are compared. Thus, using the data from 1973 and 1975 and the non-overlapping part of 1974 gives an annual production of about 75 g C/m^2, which is only 43.7% greater than in 1959–60, while using the best results from 1974 and 1975 gives an annual production of 104.24 g C/m^2, which is twice as much as in 1959–60 (Table 3). When measurements from each year are treated separately, as well as when they are pooled (1959–60 plus 1973–75), however, 3 yearly maxima seem to persist. A spring bloom occurs some time from mid Apr. to mid Juni and lasts for about 2 weeks to a month. A mid summer maximum occurs in the period mid June to late July. Finally an autumn bloom covers a span of 2 to 4 weeks from late Aug. till the end of Sept.

The size, duration and time of occurrence of the various blooms vary from year to year. The onset of the spring bloom and seemingly also the magnitude and time of culmination depend upon the extent and character of the cover of ice and snow, and upon the time of the breakup (Andersen 1977a). In 1974 as in 1959 and 1960 the ice was late in breaking (in May), the spring bloom had already to a minor degree commenced before the ice had gone for good, and the spring bloom only reached a moderately high peak by late May. In 1975, however, the ice broke already in the latter half of Apr., starting off an earlier bloom which reached an exceptionally abrupt and high peak already in the first half of May. This may also have been the case in 1973, when only net samples were taken from May to June. These are very bulky compared to samples from the corresponding period in 1974, and they much resemble the ones taken in May 1975. Whatever the cause, it implies, as shown above, that pooling of results from different years may lead to error.

In 1973, a massive and abrupt spring bloom, like the one in 1975, may have exhausted the nutrient supply to such an extent, as to impede the attainment of a sizeable bloom later in the year with relatively large and thus more nutrient demanding algae, as are seen to dominate in the main centres of production during the blooms of 1974 and 1975 (Fig. 23). There are no indications,

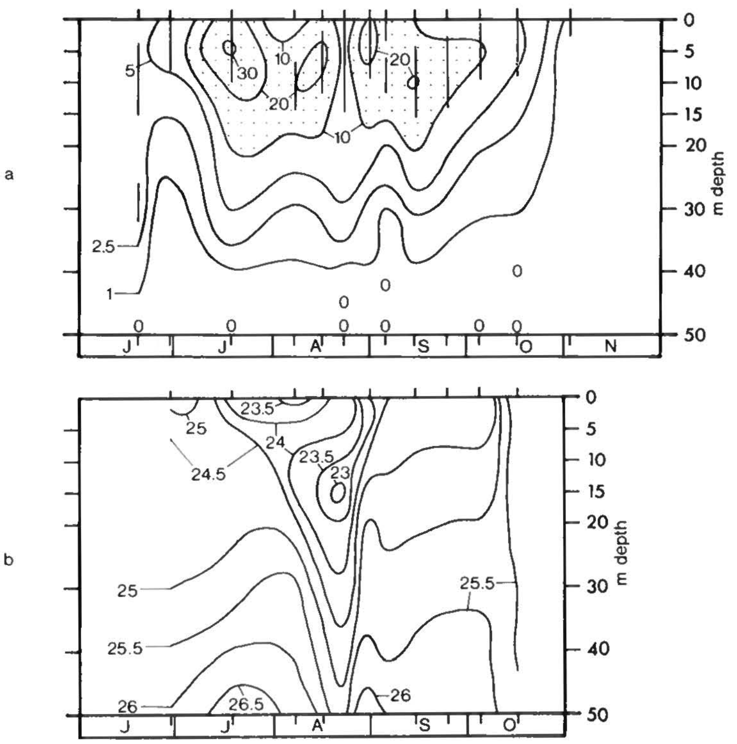


Fig. 17: Godhavn 1973. Isopleth diagrams of: a: Primary production (mg C/m³/day), verticals cover 50% of production; b: mg CO_2-C/l. Depths indicated at the right and dates marked below.

however, in late June to early July 1973 of nutrients being exhausted to any greater extent than in 1974, although they may have been in May and early June, as in 1975 (see b & c in Figs 5–7). The explanation is probably to be sought in stability (see section on stability).

An abrupt break-up (as in 1975), with a sudden increase in subsurface illumination, can give a massive phytoplankton bloom dominated by smaller diatom species which quickly exhaust the nutrient supply, whereas earlier less prominent blooms dominated by larger species develop gradually under relatively poor light conditions beneath ice free from snow (Broström & Petterson 1977). Total spring production in the different types of bloom is, however, roughly the same.

Unfortunately, since no species determinations have been made, and a fractioning of the production samples was not performed in 1973 (as in 1974 and 1975), the differences in size and species composition of the primary producers cannot be used in this discussion of the year to year variations in primary production. See, however, section on cell size.

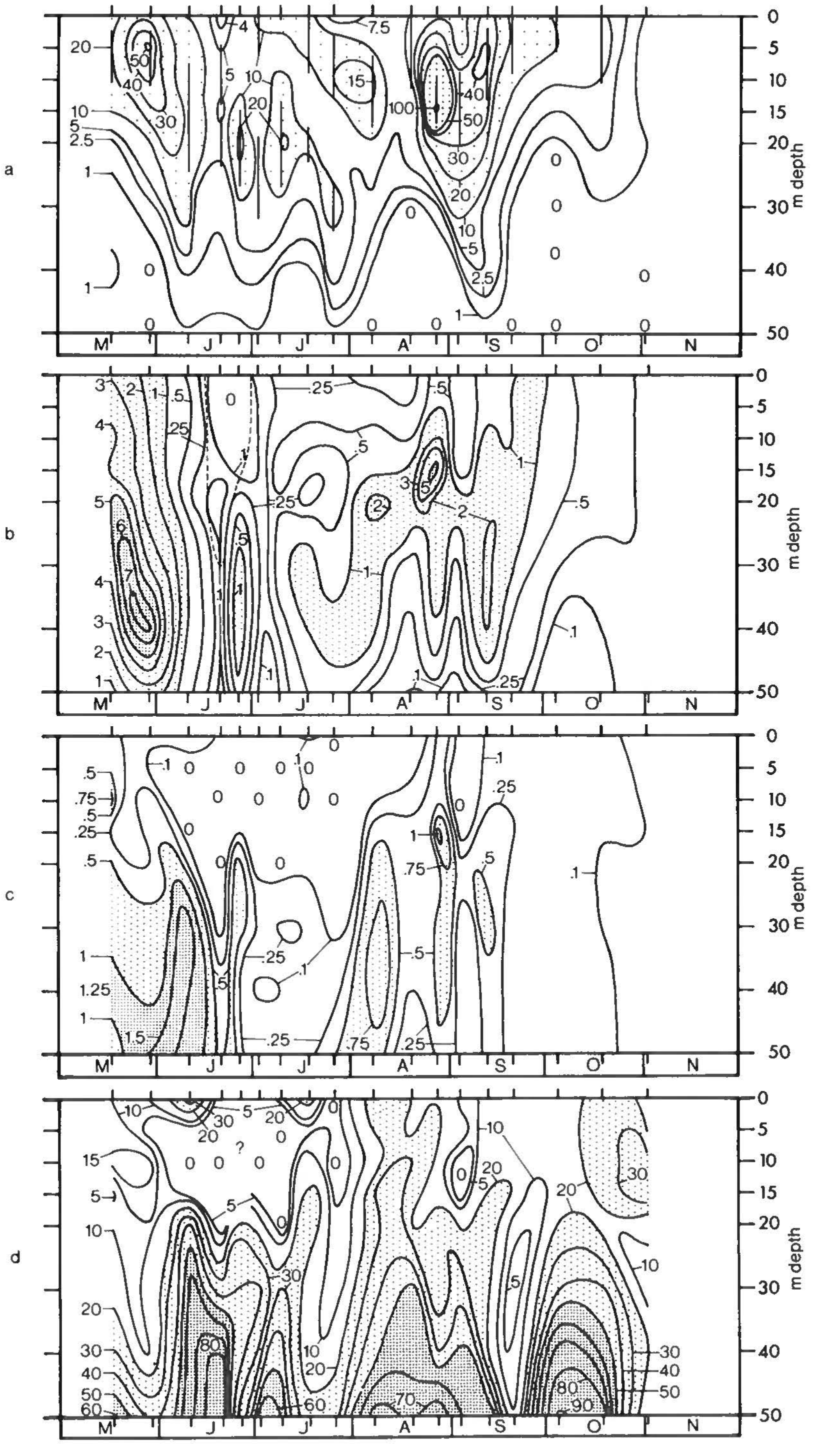
Distribution

The differences in the depth distribution of primary production in the different years kan be seen in Figs 17–19. In 1973 (Fig. 17a) production from early July to early Nov. was largely concentrated near the surface. With one exception only, the experiments show that at least 50% of total primary production occurred in the upper 15 m. The only exception was in mid June, when a minor maximum of the altogether low production at this time was found at 30 m, possibly as a last remnant from a deep layer of production, as those found in 1974 (see below).

In 1974 (Fig. 18a) production seems on 3 successive occasions to have started at or near the surface, gradually to sink to greater depth, and eventually to die out. In the latter half of May 50% of production was concentrated in the upper 10 m, though not right at the surface. Through June and July this centre of production varied both in magnitude and depth and eventually by late July, it had sunk to a depth of 30 m, after which the algal population ceased to reproduce. In early July a production maximum had again evolved near the surface, disjunct from the deeper zone of production and this upper zone gradually sank to about 15 m eventually to disappear by early Aug. Finally in mid Aug. a third bloom started at the surface and soon reached a very productive maximum with centre at about 15 m, after which part of the productivity sank and vanished by mid Sept., while some still existed nearer to the surface till well into Oct.

In 1975 (Fig. 19a) the spring bloom, occurred in a layer of intense production confined to the upper 10–15 metres and lasted for no more than about 2 weeks in the first half of May, after which productivity dropped to a

Fig. 18: Godhavn 1974. Isopleth diagrams of: a: As in Fig. 17; b: Chlorophyll *a* (mg/m^3); c: Phaeopigment (mg/m^3); d: 100 · phaeopigment/(phaeopigment + chlorophyll *a*). Dashed lines enclose pigment measurements of less than the uncertainty on the instrument.



very low level with a maximum at about 40 metres. In the beginning of June a small amount of production again occurred near the surface disjunct from the deeper layer, where more than 50% of production was still to be found.

Stability

The importance of stability with relation to primary production – compensation depth, critical depth and nutrient supply – is well known. At Godhavn the

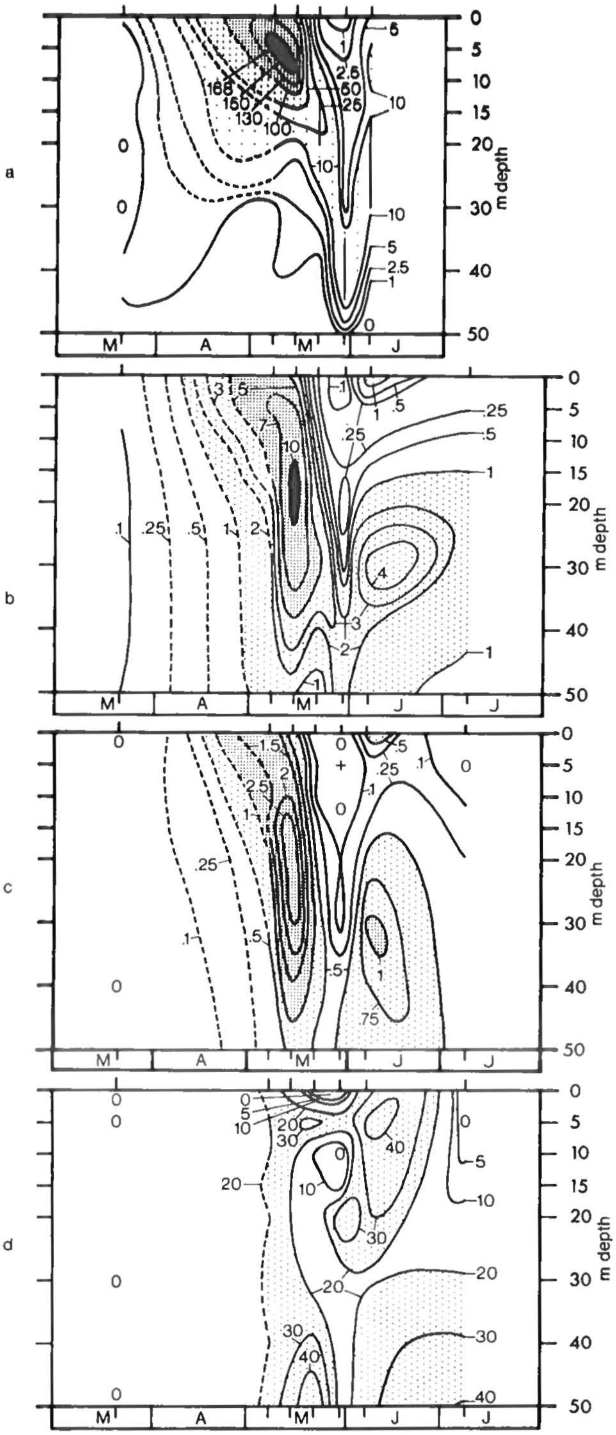


Fig. 19: Godhavn 1975. As Fig. 18.

thermo- and haloclines, established as soon as the ice breaks and developing further during the summer, cause such stable conditions to exist throughout most of the productive period – till late Sept. – that the critical depth is of major importance from Oct. till the start of the breakup of the sea ice in Apr. – early May only. The compensation depth, however, proves a very real and important boundary to primary production with a decisive effect upon the fate of the phytoplankton stock, should it come below this boundary. The stability thus limits the exploitation of nutrients to a very shallow surface layer, as described above.

In 1973 (Fig. 17a) production was relatively low, because of a relatively surface-near main discontinuity layer (Fig. 5a). During most of the summer the main halocline was located at 15–30 m, and at times down to 40 m, and it was not until the end of Sept. that discontinuities greater than 1‰ per 50 m reached below 40 m and into depths attained by less than 1% of surface transmission (Fig. 8c). During most of the productive period, in other words, unstable conditions existed right up into the euphotic zone, but beneath a discontinuity layer, and most probably this instability extended down beyond the critical depth. Thus in 1973 production was restricted to a comparatively shallow surface layer only, where nutrient deficiencies were apparent.

In 1974 the steep but shallow surface halocline (Fig. 6a), established as a result of the breaking up of and melting of the sea ice, was apparent in mid May, and production was under way (Fig. 18a) in the well lit upper 10–15 m (Fig. 9a & b) encompassed by this density gradient. It may have been a secondary spring bloom which, following a period of low illumination just prior to mid May, set in as a result of two week-long periods with high winds (Fig. 3b). These winds demolished surface stability, creating salinity gradients of less than 1‰ per 50 m in the upper 60–90 m, and they may have made some degree of nutrient replenishment from below possible. The windy periods in May–June, in any event, seem to have caused a first main halocline to be established at greater depth than was the case in 1973, namely below 30–40 m and thus below or at about compensation depth. This left the depths above ca. 20–40 m or even deeper quite unstable, but protected from mixing into deep water from May to mid Aug., affording somewhat better conditions for the utilization of nutrients upwelling in the lower parts of the euphotic zone which may have caused deeper productive zones to be established in 1974 than in 1973.

A greater predominance of easterly winds in May and June 1973 (Fig. 11D) may also, by promoting conditions of upwelling, have forced any layer of discontinuity closer to the surface. Possibly also the fewer periods with winds over 2 knots (Fig. 11C), the longer periods with winds of less than two knots (Fig. 11B) and in all a longer total blowing time for winds of less than 2 knots (Fig. 11A) may have caused less turbulent mixing, contributing to a more surface-near positioning of the major halocline in 1973 than in 1974.

The earlier, more intense spring bloom in 1975 occurred in the upper 10–15 m as in 1974 and in a relatively weak salinity gradient, before the main sur-

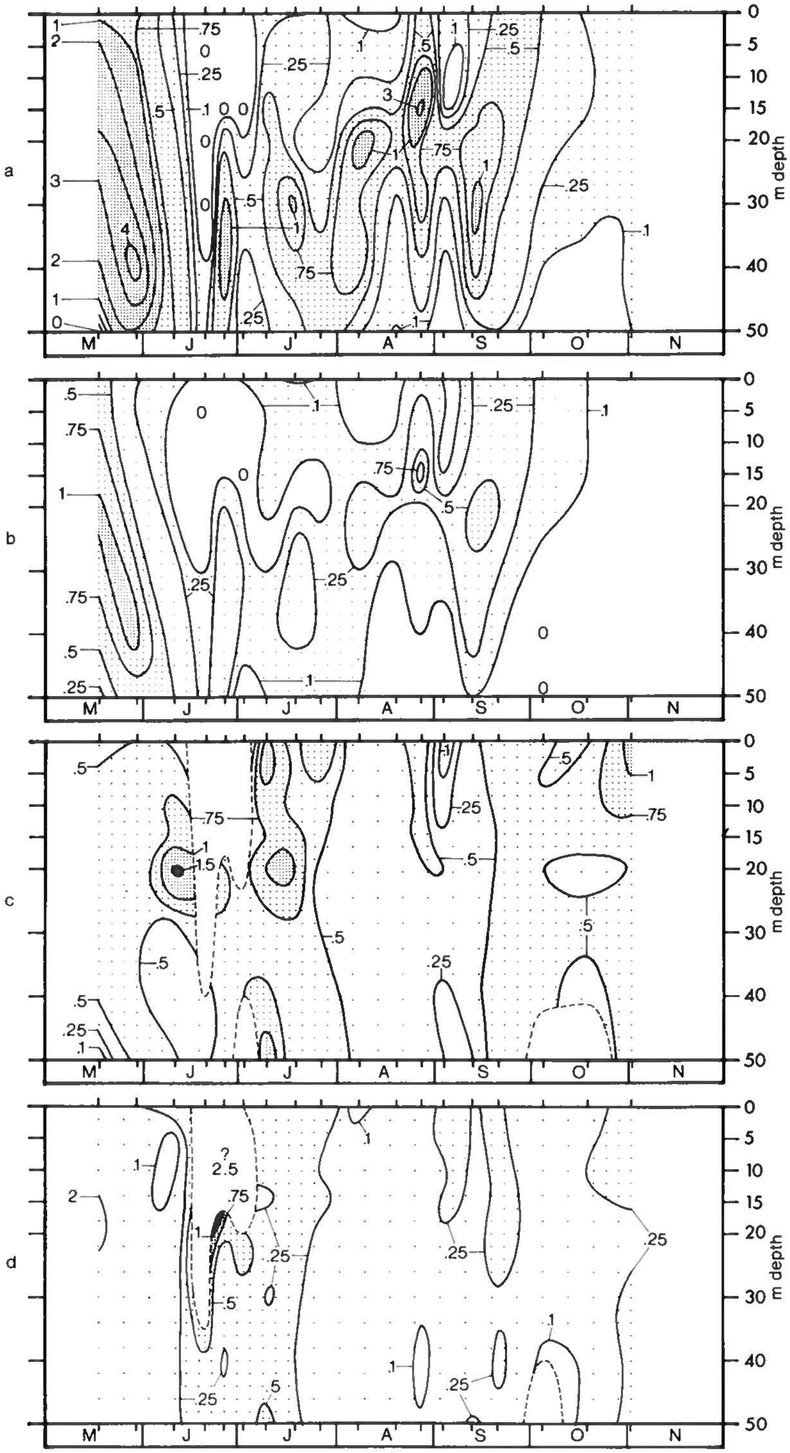


Fig. 20: Godhavn 1974. Isopleth diagrams of: a: Chlorophyll *c* (mg/m³); b: Chlorophyll *b* (mg/m³); c: Chlorophyll *c*/chlorophyll *a*; d: Chlorophyll *b*/chlorophyll *a*. Depths indicated at the right and dates marked below.

face discontinuity had been established as a result of the breakup and the melting of the sea ice, and at a greater depth than this. As soon as this halocline was established production quickly decreased and became concentrated at even greater depth as a result of the adverse effect of stability upon nutrient replenishment by mixing in the surface layers.

Phytoplankton pigments

The distribution of chlorophyll *a* (measured in 1974 and 1975 only) (b in Figs 18 & 19) is strikingly different from that of the main centres of primary production, and there seems to be greater continuity than one would expect from the production measurements (a in Figs 18 & 19). The main concentrations of chlorophyll *a* are largely found beneath the most productive layers, except in the early spring and in the fall. In fact as much as 97% (6–97%) of total chlorophyll *a* in the upper 50 m can be found below the euphotic zone, defined by the depth to which 1% of surface transmission goes. Nevertheless, there is a definite positive correlation between primary production per m^2 and chlorophyll *a* per m^2 in the upper 50 m ($r = 0.73$; $P < 0.001$), but due to the often greatest concentration of chlorophyll *a* below the euphotic zone correlation in this zone alone is not as good ($r = 0.63$; $P < 0.001$). Part of the chlorophyll found below the euphotic zone degrades into phaeopigment, the largest concentrations of which usually occur below and at a later date than the chlorophyll *a* maxima (c in Figs 18 & 19).

The production maxima in the spring of 1975, and in the spring and fall of 1974, each have their corresponding and prominent chlorophyll *a* maxima. In the start of the early spring bloom in 1975 the production and chlorophyll *a* maxima coincide in time and space, but at the height of the spring blooms of this year and of 1974 the chlorophyll *a* maxima are found at increasingly greater depth and eventually reach depths attained by less than 1% of surface transmission. The 1% depth is relatively shallow due to great surface turbidity only in part caused by the phytoplankters themselves, but it is well beneath the main centre of production, and retention of the algae there proves fatal to survival and to continued production.

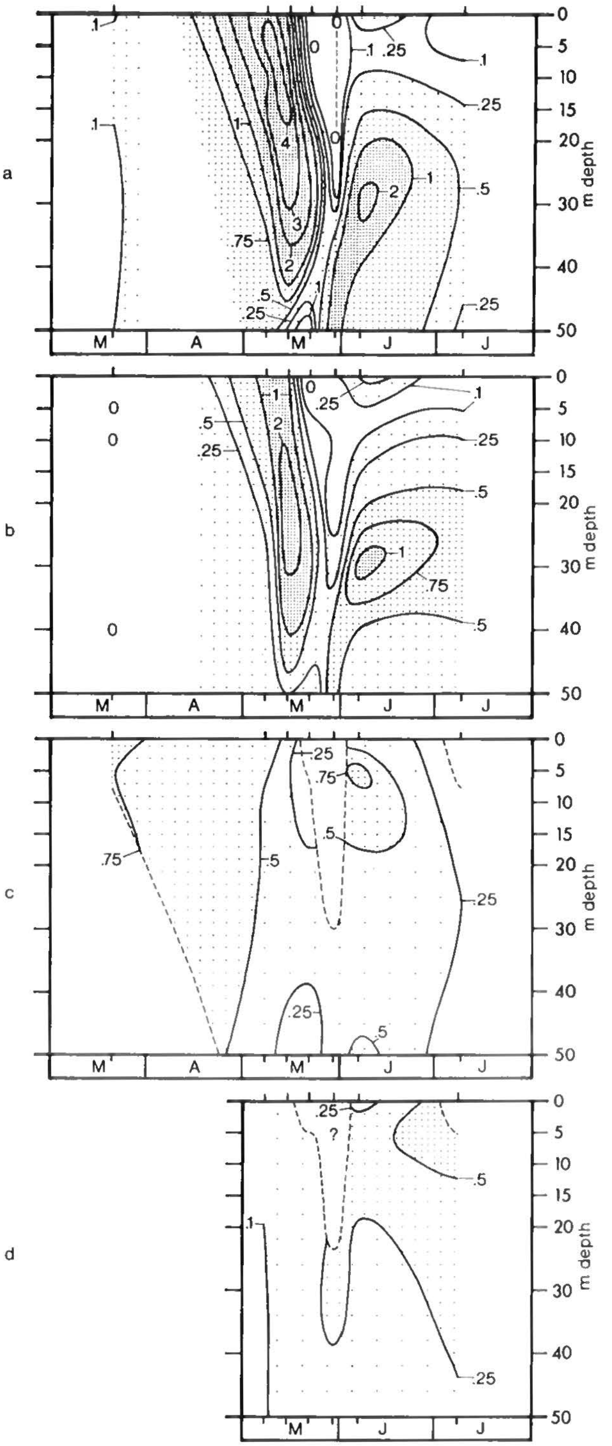


Fig. 21: Godhavn 1975. As Fig. 20.

Although the greater part – more than 80% – of the chlorophyll *a* is viable at this time – less than 20% has been oxydized into phaeopigments (Fig. 18d) – the ultimate fate of the algae now trapped in virtual darkness below the euphotic zone by the discontinuity layer which has evolved following the breaking up and melting of the sea ice in May, is consumption by herbivorous zooplankters, or bottom invertebrates, or perhaps degradation into phaeopigments even before this. In both years the algae seem to sink during mid and late May and the result is a rise in phaeopigment concentration below 20 m. This is best seen in 1974, and relative concentrations of more than 80% phaeopigments are found at 40–50 m in mid June of that year. In late June, and in July–Aug. 1974, moderate concentrations of chlorophyll *a* are found below the major centres of production, and here an algal population seems to subsist continually through July and Aug. The highest percentages of phaeopigments exist in the sparsely populated depths below the main concentrations of chlorophyll *a*. In late Aug., when surface heating and freshening has ceased, and vertical mixing is allowed to reach well below the surface, the main algal population is again allowed to come closer to the surface, and a brief fall bloom coeicides quite well with the chlorophyll maximum, as well as with the main concentration of phaeopigments, since here the penetration of light is less inhibited by non-phytoplankton turbidity.

The cause of degradation of chlorophyll *a* into phaeopigment has largely been attributed to the action of herbivorous zooplankters (Lorenzen 1967, Glooschenko 1972), while Spence & Steven (1974) through 3 years of investigations in the Gulf of St. Lawrence were able to find no correlation between phaeopigment concentration and the occurrence of zooplankters – perhaps because all species were included.

At Godhavn there is no correlation between the concentrations of chlorophyll *a* and of phaeopigment. This suggests that it is not just passive sinking which causes chlorophylls to degrade. Phaeopigments show no significant negative correlation to illumination. In fact, relative concentrations are often greater at the immediate surface, due to the deteriorative action of light, than a few metres deeper. It is also notable that phaeopigment content – both absolute and relative – is usually very low, where P/B ratios are at their highest (compare c & d in Fig. 18 with Fig. 28a).

Green fecal pellets – from copepods – counted on the ^{14}C filters from Godhavn 1973 show a distribution which roughly corresponds to that of the phaeopigments the two following years, namely with greatest concentrations well below the production maxima – except in late Aug. as in 1974 – and if any, then always at 50 m. Accordingly, the deterioration of chlorophyll *a* into phaeopigment at Godhavn seems best attributed to feeding by herbivorous zooplankters, and the sinking of their fecal pellets – known to contribute with up to 99% to vertical mass flux at rates of 50–950 m per day in other seas (Cherry & Higgo 1978) – constitutes a major transport mechanism for degraded chlorophylls away from the photic zone.

Profiles of chlorophylls *b* and *c* are generally quite congruent to those of chlorophyll *a* (compare a and b in Figs 20 and 21 with b in Figs 18 and 19). The abundance of the three chlorophylls *a, b* and *c* is on the average as 10:2:5. The mean concentrations in mg/m^3 are 1.326 (s.d. = 1.978 = 149%), 0.289 (s.d. = 0.401 = 139%) and 0.671 (s.d. = 0.932 = 139%) respectively. The concentration of chlorophyll *a* is the most variable, and it is primarily variations in the concentration of chlorophyll *a* that cause the variations in the ratios chl. *c*: chl. *a* and chl. *b*: chl. *a*. The highest ratios occur where the P/B ratios are also very high, and where concentrations of chlorophyll *a* and production values are very low in June and July 1974 and less so in 1975.

Cell size

During most of the productive season at Godhavn production is dominated by nannoplankton (< 56μ). The same has been reported by other authors (Yentsch & Ryther 1959, Malone 1971a & b, McCarthy et al. 1974, Berman 1975), especially for oceanic waters. Malone (1971a), however, found less dominance by nannoplankton in coastal waters. At Godhavn micro-

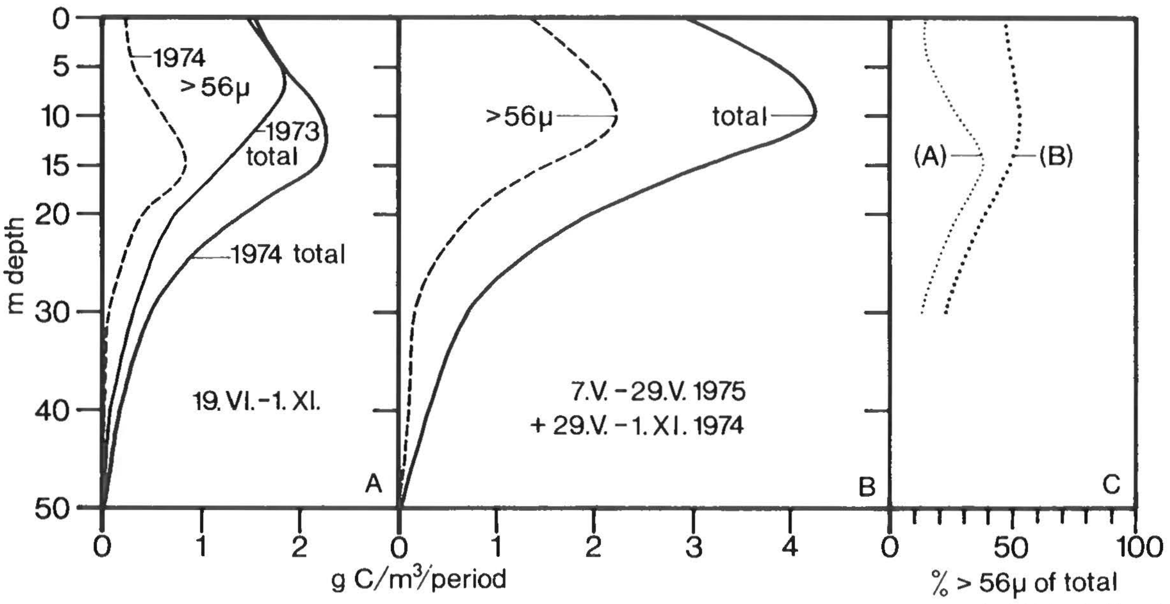


Fig. 22: Godhavn primary production. A: Profiles (g C/m^3/period) from corresponding periods in 1973 and 1974 (excluding the spring bloom) and for microplankton (> 56 μ) in 1974. B: Profiles for total and microplankton production during the spring bloom of 1975 and the remaining productive period of 1974. C: Percentage of production covered by microplankton in A and B marked (A) and (B) respectively.

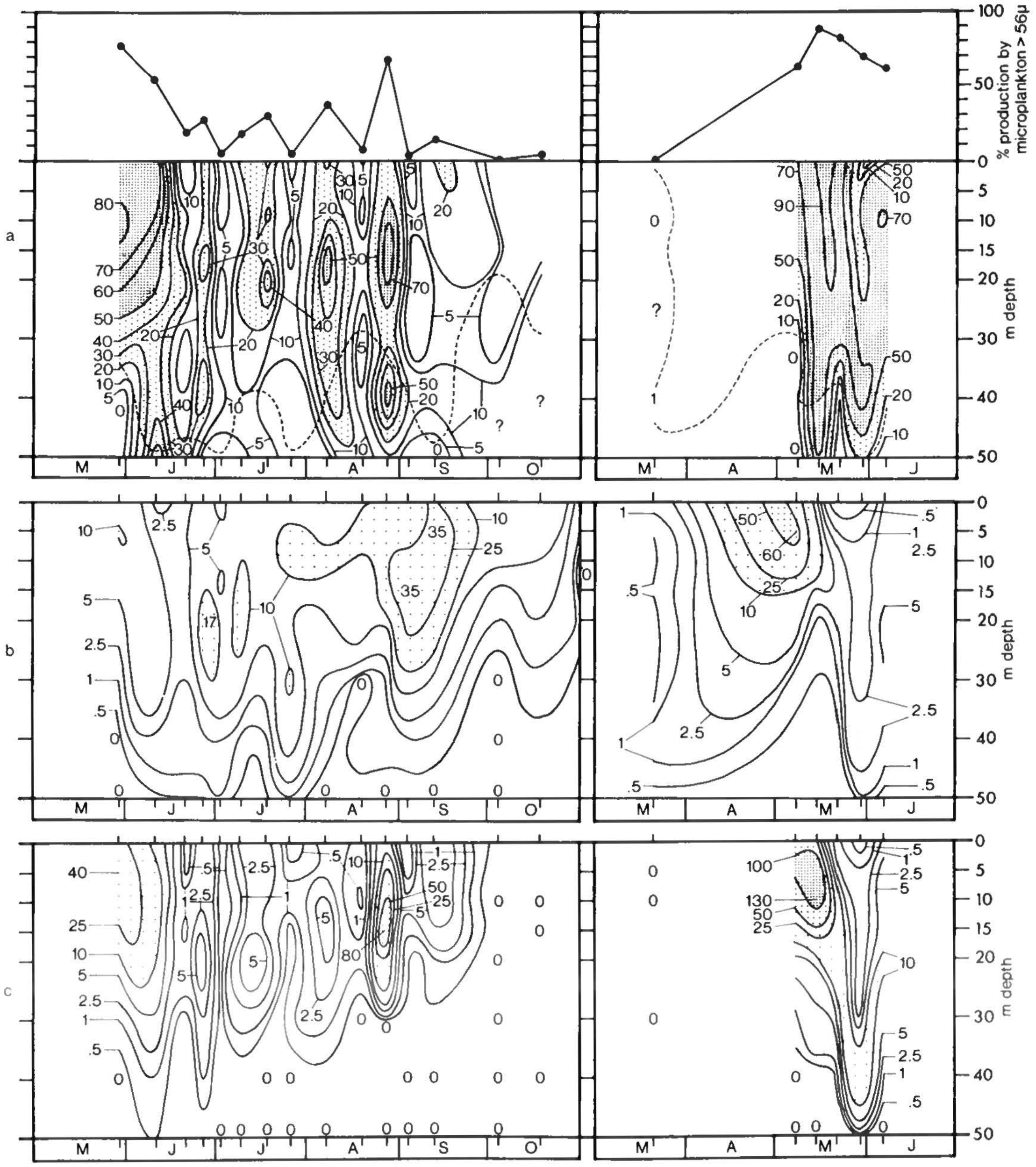


Fig. 23: Godhavn 1974 (left) & 1975 (right). a: Percentage of primary production in upper 50 m by microplankton (> 56 μ) (top), and variation with depth (bottom). b: Primary production (mg C/m^3/day) by nannoplankton (0.2–56 μ). c: Primary production (mg C/m^3/day) by microplankton (> 56 μ). Depths indicated at the right and dates marked below.

plankton or netplankton (> 56 μ) can make up about 50% of the annual production per m^2, and from about 20 to 50% of production per m^3 (Fig. 22). The microplankton is to a great extent responsible for the fluctuations in primary production through the year. It dominates production in the major blooms and especially in the spring blooms, where as much as 90% of production per m^2 and even more per m^3 is microplankters (Fig. 23). Total production per m^2/day thus correlates far better to microplankton production than to nannoplankton production (Fig. 24) and microplankton is a major factor determining the vertical distribution (Fig. 22).

An experiment made at Godhavn in July 1977, where both chlorophyll and production were divided into nanno and micro fractions at 30 μ, shows that when

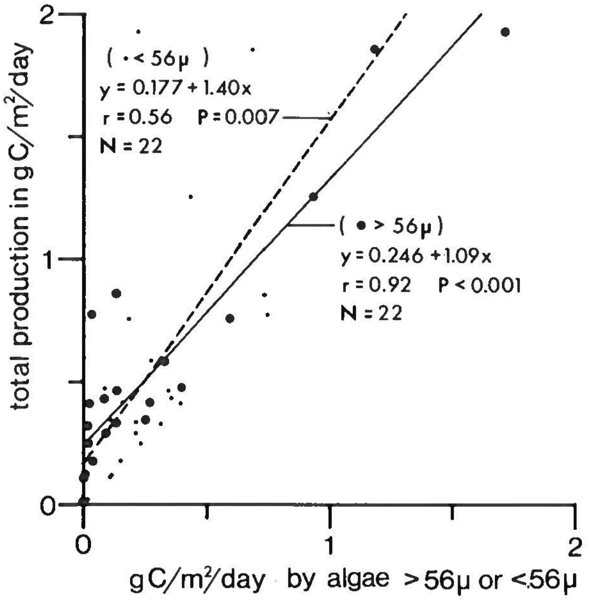


Fig. 24: Godhavn 1973–75. Correlation between total production, and microplankton (> 56 µ) and nannoplankton (0.2–56 µ) (g C/m²/day).

production of microplankton as compared to nannoplankton is at its greatest, it is, at least in part, due to a better P/B ratio and not necessarily to a more favourable distribution of the larger phytoplankters (Fig. 25). In this experiment the microplankton comprised from 0 to 37% of total chlorophyll *a*/m³, whereas it represented from 3.56 to 40.9% of production. At the level of greatest microplankton production (6.23 mg C/m³/day at 20 m) this production comprised 40.9% of total production, while only 4.35% of the chlorophyll was found in microplankton, and P/B was thus 15.23 times greater for the microplankton than for the nannoplankton which is the greatest difference found (Table 4). In spite of this, an overweight of nannoplankton in the upper 50 m (72.4%) and a more favourable (more even) distribution of this causes an overweight of production by nannoplankton (79.1%) – a typical situation outside the major blooms.

The reason for the general overweight of nannoplankton in spite of a lower P/B rate is probably the competitive advantage that these smaller cells have in a faster nutrient uptake rate. Friebele et al. (1978) for example found that estuarine nannoplankton of Chesapeake Bay (phytoplankters < 65 µ) had an uptake rate for orthophosphate 11.29 times greater than that of microplankton (> 65µ). Eppley et al. (1969) showed that larger species have higher K_s values than smaller species, but that they also grow slower, which does not seem to be in accordance with the results from Godhavn. However the effect of nutrient uptake rates on specific growth rates is modified by variations in efficiency of light utilization by the phytoplankton species, at different light intensities, and Parsons and Takahashi (1973) have developed a model which predicts that small species will outgrow larger species in all environments *except* those where nutrient levels and light intensities are high. This is in compliance with the dominance of microplankton production in the blooms at Godhavn which occur in the spring, and whenever upwelling brings about nutrient replenishment to the euphotic zone later in the year – as also reported in the California Current (Malone 1971b).

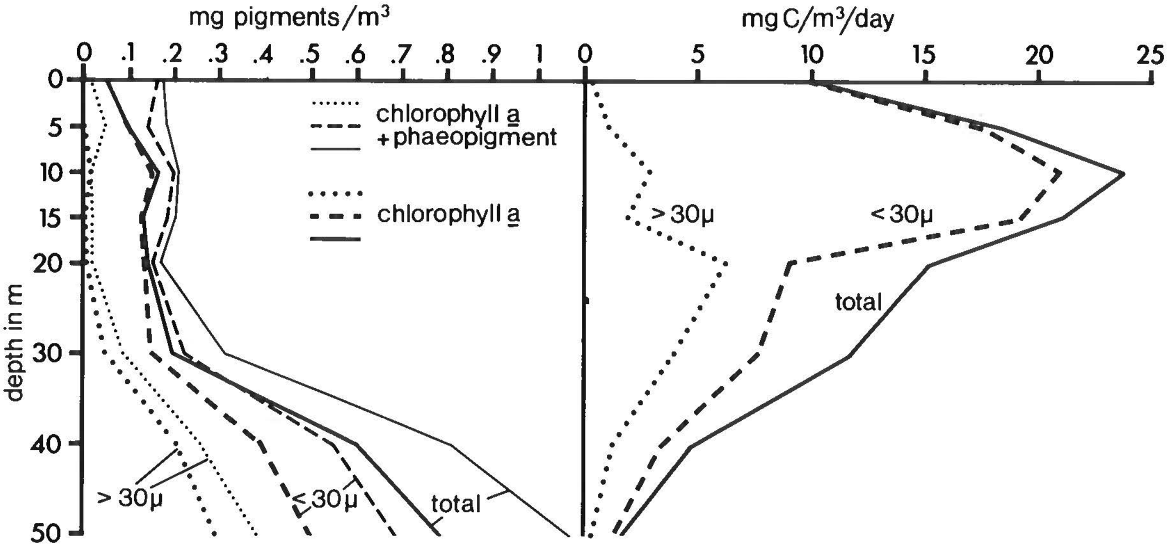


Fig. 25: Godhavn, July 1977. Profiles of a series (depths indicated at the left) of 8 measurements of primary production (mg C/m³/day) and pigments (mg/m³) showing total, micro-, and nannoplankton. See Table 4 and text.

Table 4: Relations between microplankton ($> 30\ \mu$) and nannoplankton ($< 30\ \mu$) with respect to biomass (B) measured as chlorophyll *a*, to production (P) measured as daily fixation of carbon, and to P/B.

depth m	C $> 30\ \mu$ %	chl. *a* $> 30\ \mu$ %	P/B total	P/B $> 30\ \mu$	P/B $< 30\ \mu$	P/B $> 30\ \mu / < 30\ \mu$
0	3.56	0	212.71		205.14	
5	5.50	0	191.48		180.94	
10	12.16	9.99	146.93	178.95	143.38	1.25
15	8.89	1.71	163.43	851.82	151.49	5.62
20	40.92	4.35	110.34	1038.57	68.51	15.23
30	34.63	24.13	60.02	86.12	51.71	1.67
40	26.72	34.54	8.08	6.25	9.05	0.69
50	21.42	36.98	2.09	1.21	2.60	0.46

Illumination

Primary production is restricted almost exclusively to depths where the subsurface illumination as measured with a selenium cell and green filter is not less than 1–0.1% of surface transmission.

This corresponds to daily light sums of not less than about 0.1–0.01 gcal. green light (500–550 nm)/cm^2 (compare Figs 8–10 with Figs 17–19). From these it is evident also that light inhibition occurs at the surface, where nutrients are usually found in greater concentrations than a few metres deeper. From Fig. 33a it is evident that production is limited by low light intensities, at least when these add up to daily light sums (500–550 nm) of less than 0.5 gcal/cm^2. Above this production rates are extremely variable within narrow regimes of daily light sums and maximum rates are possible already at 1–2 gcal/cm^2/day.

Total production per m^2 is roughly correlated negatively ($r = \div 0.43$; $P = 0.048$) with the depth of the euphotic zone, defined as the depth to which 1% of surface transmission goes, and the concentration of chlorophyll *a* in the euphotic zone is likewise correlated negatively with this depth ($r = \div 0.45$; $P = 0.040$). This shows that low production is associated with low concentrations of chlorophyll, causing low self shading (compare Figs 8–10 with 17–19).

Nutrients

Although production is not least, where the concentration of PO_4-P is lowest, there is a general rise in production (P) means with rising concentration of PO_4-P from 0.05 to about 0.18 μgat/l which is the concentration at which P/B rates on the average are highest (Fig. 37). The highest production rates are reached at about 0.35 μgat/l, above which production drops abruptly reaching its lowest values at concentrations of 0.4–0.95 μgat/l. There is no general rise in production rates with rising concentrations of NO_3-N. Production is fairly constantly low at concentrations from 0.005 to about 0.05 μgat/l but also at about 0.25 μgat/l and again definitely at concentrations above about 1 μgat/l due to low light intensities occurring at the depths in question.

A comparison of the centres of production (a in Figs 17–19) with the depletion of nutrients (b & c in Figs 5–7) reveals that nearly all of the production occurs where the concentrations of nutrients are very low or where they begin to increase markedly with depth while illumination at the same time drops to near compensation values (Figs 8–10). Thus in 1973, when nearly all production was restricted to the upper 15–20 m, and at the same depths in 1974 from late June to early Aug., when a centre of production was found there, separated from a deeper layer of production, the main centres of production represented by the 50% lines (a in Figs 17 & 18) occurred at concentrations of PO_4-P which were less than 0.05–0.1 μgat/l and even as low as 0.02 μgat/l and at concentrations of NO_3-N which were less than 0.2 μgat/l and at times entirely below 0.1 μgat/l, even reaching less than 0.005 μgat/l. In 1974 and the spring and early summer of 1975, however, most of the main centres of production represented by the 50% lines (a in Figs 18 &19) occurred in the transitional zone, where the concentration of PO_4-P changed as much as from 0.05 to 0.4 μgat/l, and the concentration of NO_3-N changed from less than 0.1 to 2 μgat/l. The changing depths of production maxima follow the undulating depths of these concentration levels which vary due to upwelling, as shown. It is during the periods of major upwelling that the non spring blooms occur. Only in early spring and in late fall did a major part of the low production at that time take place at higher nutrient levels.

While the concentrations of both NO_3-N and PO_4-P are quickly reduced during the first spring bloom, the depletion of NO_3-N is faster and more thorough than that of PO_4-P. The isopleth diagrams of NO_3-N/PO_4-P in fact resemble those of NO_3-N, since minimum values of NO_3-N/PO_4-P drop from about 12 to 0 (Fig. 26). Where the concentration of NO_3-N is below about 0.08 μgat/l, the concentration of PO_4-P is generally greater than that of NO_3-N. At concentrations of about 0.08–0.17 μgat/l, at which production gradients are often greatest, the two nutrients stand about equal, while above this the concentration of NO_3-N rises most abruptly, and it is always greatest at concentrations

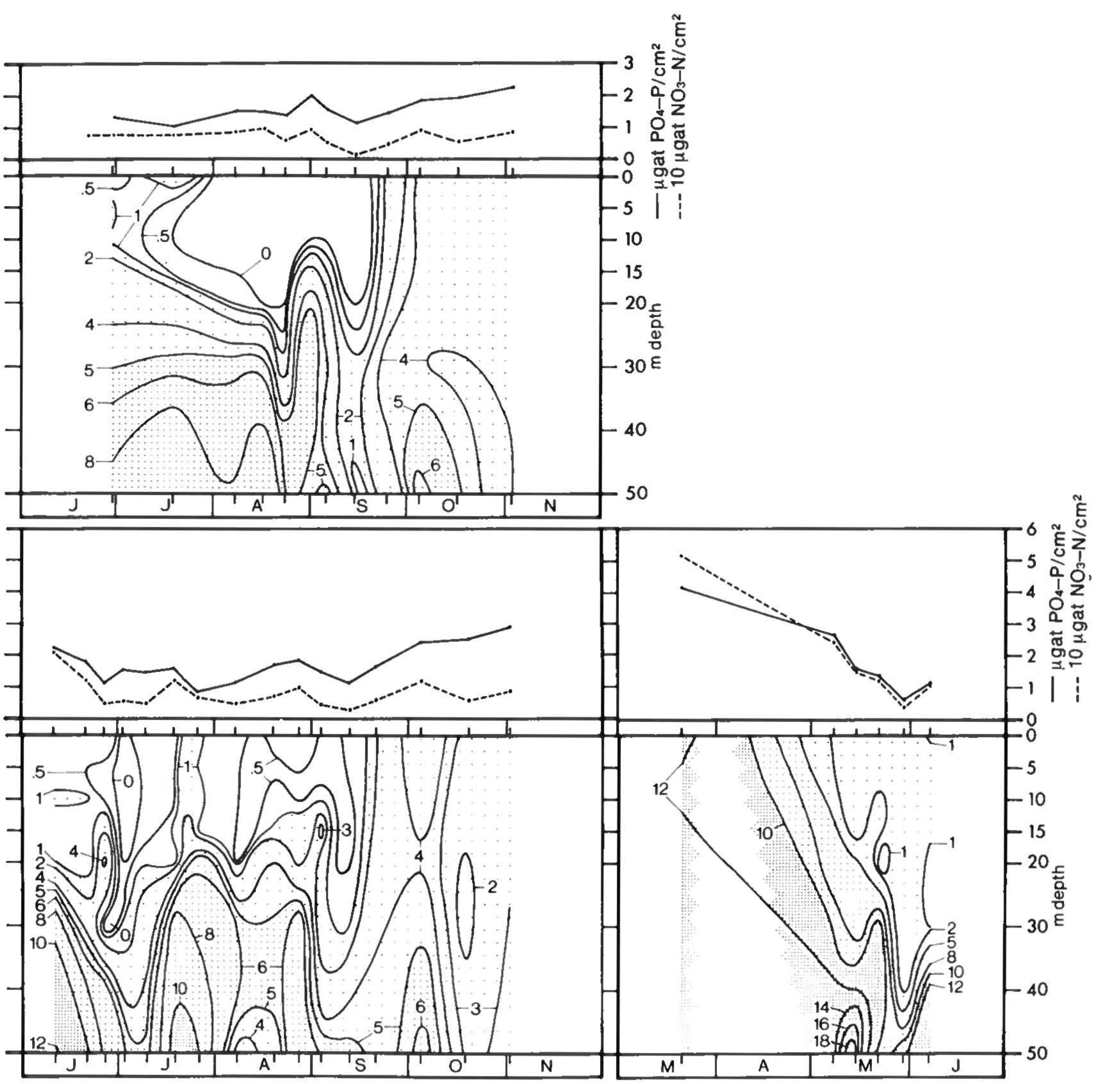


Fig. 26: Godhavn 1973 (top), 1974 (bottom left), and 1975 (bottom right). Nutrients. Curves of total in upper 50 m, and isopleth diagrams of the ratio NO_3-N : PO_4-P (µgat/liter). Depths indicated at the right and dates marked below.

above 0.3 µgat/l (Fig. 27). The figure also shows that the concentration of NO_3-N varies far more than that of PO_4-P. This also applies to the total concentrations in the upper 50 m, although they generally rise and fall simultaneously – with exceptions, however, as in July–Aug. 1974 and in the first half of Oct. in both 1973 and 1974, when the increasing instability promoting greater vertical mixing in the upper 50 m is accompanied by a slight rise (about 5%) in the total concentration of PO_4-P, while the total concentration of NO_3-N is reduced by about 50% (Fig. 26).

Correlations

Correlations involving daily production of carbon in mg/m^3 (P), biomass measured as chlorophyll *a* in mg/m^3 (B), green light (500–550 nm) in $gcal/cm^2/day$ (L), and NO_3-N and PO_4-P in µgat/l (NO_3 and PO_4) are, apart from the intricate interrelations between some of them, primarily hampered by the fact that the phytoplankton material involved consists of plankton populations of changing species composition, and further by temperature effects, light inhibition effects and adaptations to different light intensities.

P/B, P/B/L, primary production and chlorophyll a

There is no correlation ($r = 0.16$) between P and P/B if all series from 1974 and 1975 are pooled (1 in Fig. 29). If, however, the fall bloom (27 VIII 1974) and the spring bloom (7–14 V 1975) are treated separately (3 in Fig. 29) there is some degree of correlation ($r = 0.51$) for these 3 series and for the remainder ($r = 0.47$) (2 in Fig. 29). These blooms with their dominance of production by microplankton (> 56 µ) over nannoplankton

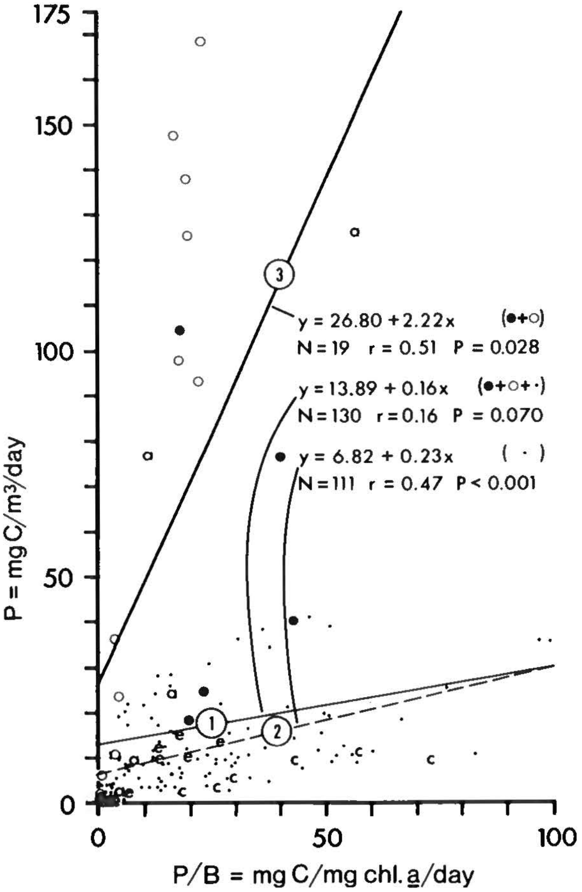


Fig. 29: Godhavn 1974 and 1975. Correlations between primary production, P = mg C/m³/day, and production efficiency, P/B = P/mg chlorophyll *a*/m³, in all experiments (1), in spring bloom (open circles) plus fall bloom (filled circles) (3), and outside the blooms (dots) (2) = (1) ÷ (3). August series from Egedesminde (e), Christianshåb (c), and off Atâ Sund (a) are plotted.

production (P). At certain depths during the major blooms only, there is some degree of positive correlation between P/B/L and chlorophyll *a* (B), namely at 5–15 m on 27 Aug. 1974 (r = 0.97, P = 0.17), at 0–20 m on 14 May (r = 0.94, P = 0.02) and at 0–30 m on 21 May (r = 0.99, P < 0.001) as well as at 15–30 m on 6 June 1975 (r = 0.99, P = 0.08). At these depths, where illumination was sufficient to ensure a net production, a regular absolute rise in P/B/L efficiency with depth accompanied a regular absolute rise in the concentration of chlorophyll *a* (B) (caused by the sinking of algae) to the highest concentrations encountered on each date, as well as in the series put together. In most of the other series the P/B/L efficiency rises independent of chlorophyll *a* concentration and reaches a peak before the chlorophyll *a* maximum is reached.

The efficiency maxima – both P/B and P/B/L – often occur later than the production (P) maxima as well as the chlorophyll *a* (B) maxima. This may be because it takes a certain amount of time for grazers to locate the major centres of production, where they, along with bacteria evolving with them, may promote a better recycling of nutrients, which is not discernible merely by measuring the ambient concentrations of nutrients. Then again large concentrations of different algae may by excretion of certain substances impede the growth of each other or even of themselves.

P/B and light

Due in part to light inhibition, the greatest P/B ratios do not occur at the surface (a & c in Fig. 28). Inhibition and/or shade adaptation seem to exist from the surface, where green light (500–550 nm) sums are 25.6 to 2.6 gcal/cm²/day, down to between 5 and 20 to 30 m, where light sums are between 12.35 and 0.75 to 0.27 gcal/cm²/day (Fig. 32: 1 & 2). The relative change in P/B ÷ the relative change in daily light sum is positive in this light regime, and there is no correlation to changes in concentrations of NO_3-N or PO_4-P. At times this also occurs at depth intervals well below the surface, from 10–20 m (6.9–0.18 gcal/cm²/day) to between 15 and 20 to 30 m (between 2.8 and 0.20 to 0.04 gcal/cm²/day). The total regime of daily light sums, where photoinhibition may occur is thus between 25.6 and 0.20 to 0.04 gcal/cm²/day, at depths from the surface down to 20–30 m. A rise in concentrations of NO_3-N and/or PO_4-P, possibly along with a drop in light inhibition and/or a change in shade adaptation, is furthermore responsible

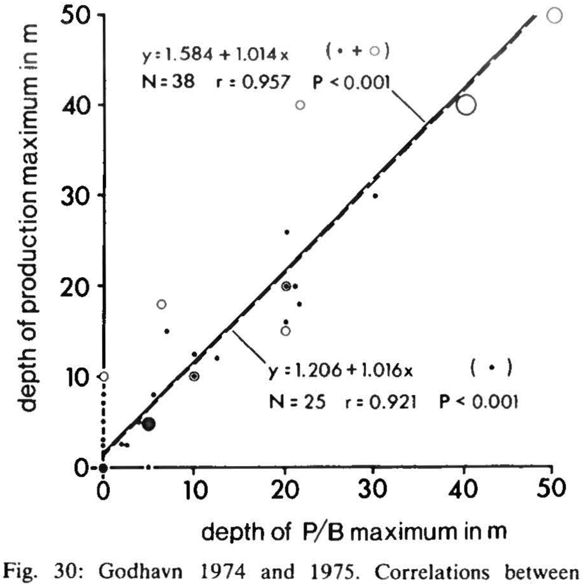


Fig. 30: Godhavn 1974 and 1975. Correlations between depths of maximum primary production, P = mg C/m³/day, and depths of maximum production efficiency P/B = P/mg chlorophyll *a*/m³.

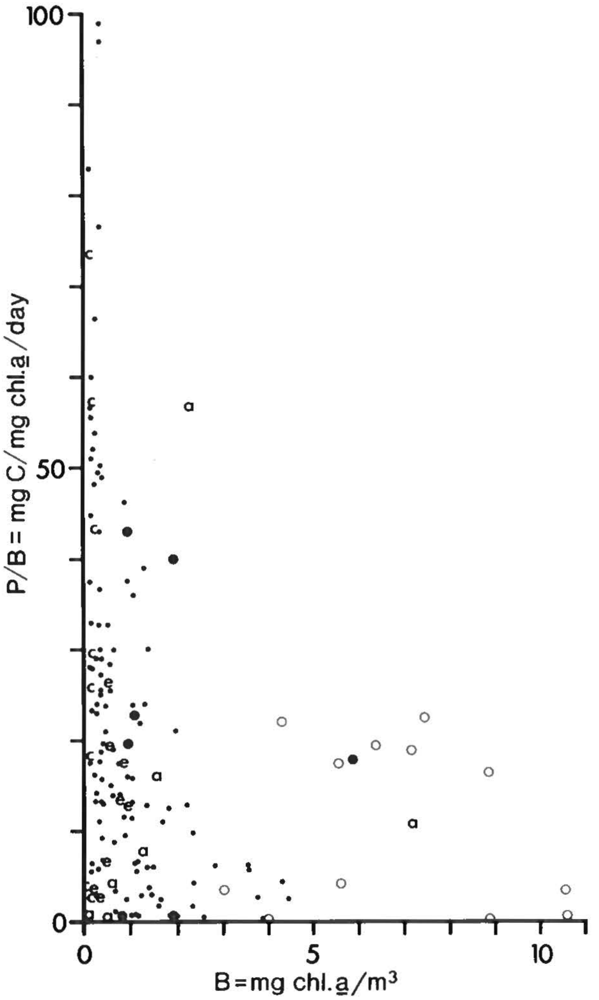


Fig. 31: Godhavn 1974 and 1975. Biomass, B = mg chlorophyll *a*/m³ plotted against production efficiency, P/B = mg C · m^{-3} · day^{-1}/B. Data from spring bloom (open circles), fall bloom (filled circles), and outside the blooms (dots), and from Aug. series at Egedesminde (e), Christianshåb (c), and off Atâ Sund (a).

for a similar positive change with depth in P/B relative to changes in daily light sum, as far down as to between 20 and 40 to 50 m, where light sums are only between 0.90 and 0.16 to 0.007 gcal/cm²/day (Fig. 32: 3).

The drop in efficiency of utilization of light energy with increasing illumination is evident from b & d in Fig. 28. Actually, the deleterious effects of light probably occur in the upper 5–10 m only, however, judging from the curve in Fig. 33b. In the interval 0.1–10 gcal green light/cm²/day, P/B shows – the year taken as a whole – a reasonable degree of correlation to the $\log^{10}$ of the daily light sum – considering the depth interval covered, and the time span involved, with changing phytoplankton populations, and nutrient concentrations. In this light regime the P/B curve thus quickly levels off reaching close to maximum rates already at 2–3 gcal/cm²/day, whereas it is well above 7 gcal/cm²/day that possible inhibition first seems to make P/B drop. Corresponding to the steep rise of the curve at small light sums in Fig. 33b, Fig. 33c demonstrates that light is best utilized at the low intensities giving these small sums, at depths where nutrients are always plentiful. On the average, however, the P/B maxima are found at higher light intensities giving daily light sums of about 5 gcal/cm².

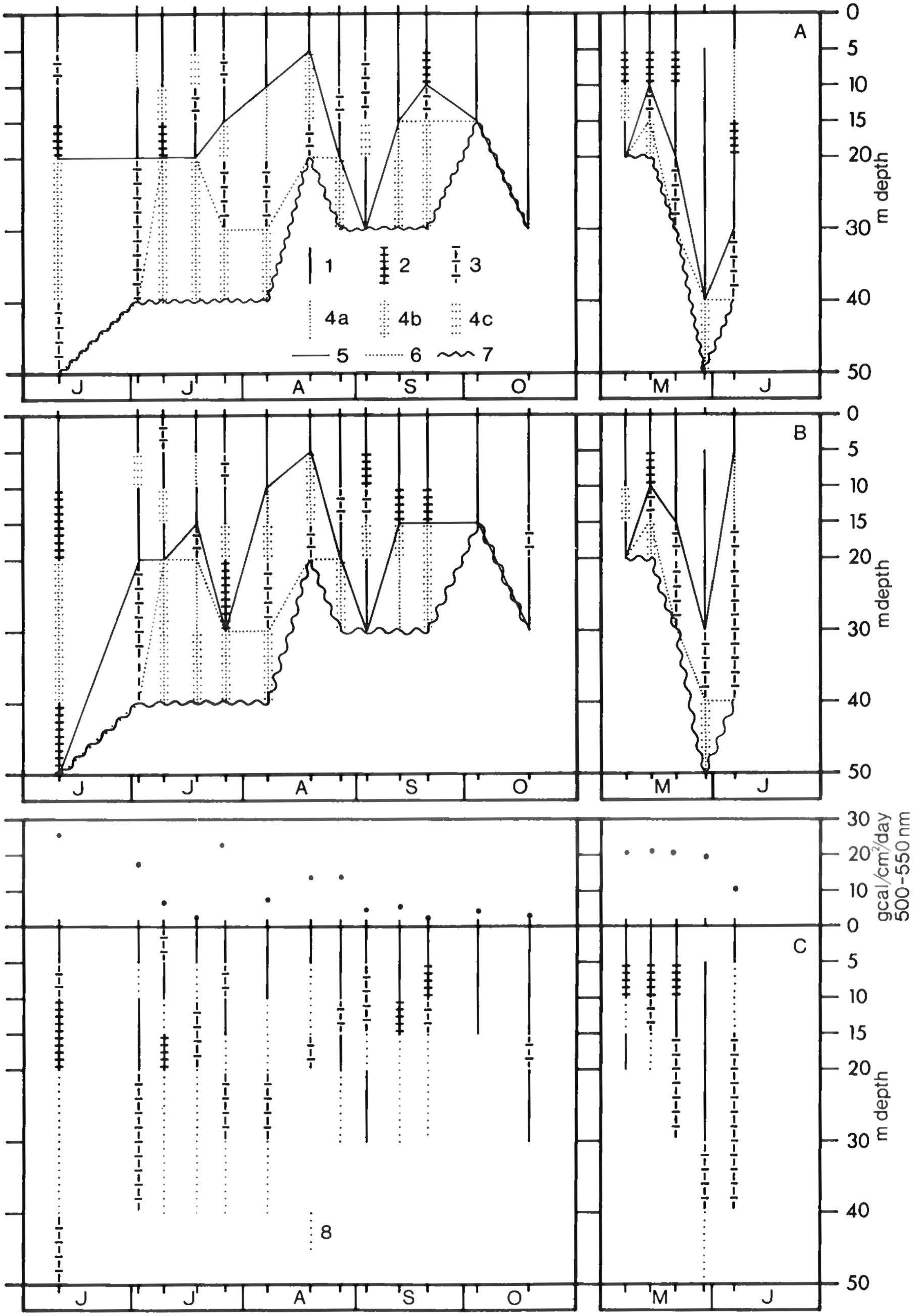
P/B, light and temperature

Though the greatest production efficiencies (P/B/L) are attained at 2–5°C, there is no general preference of temperature. P/B/L efficiencies are always low in the upper 5–15 m from late June to early Sept., when temperatures are always > 5°C, and NO_3-N and PO_4-P are found in their lowest concentrations. In fact, some of the greatest depth to depth variations in P/B/L as well as in P/B efficiencies occur under the most unstable conditions with little or no differences in temperature as in Sept. 1974, and in early May 1975. This must be because algae under such circumstances constantly meet new light conditions, to which they have to adapt themselves.

Plotting the temperature against the daily light sum (500–550 nm), found where the P/B efficiency maxima occur – one or two on each date – gives a picture of changing efficiency maxima occurring at different temperatures and in different light regimes (Fig. 35). The gradually sinking efficiency maxima accompanying the gradually sinking early spring bloom of 1975 occurred at ÷ 1.35 – 1.25°C. The following late spring – early summer blooms of the same year and of 1974, where it gradually sank below the surface, had P/B maxima occurring at about equal temperatures (1.8–3.2°C and 2.1–4.2°C respectively). The P/B of the P/B maxima did not seem to be affected in any consistent manner by the changes in illumination, although these changes were rather great, and the deeply located summer population finally died out or disappeared under light conditions which had formerly afforded quite good P/B efficiencies. The P/B maxima of the following two blooms, the midsummer surface bloom (b) and the fall bloom (c) – both, as it seems, generated from the surface – occurred at temperatures of about 4–9°C and 4.75–7.25°C respectively. The latter fall bloom died out or disappeared (c13 in Fig. 35) under roughly the same light conditions as the late spring bloom in 1974 (a9 in Fig. 35), but at temperatures about 2.5°C higher.

P/B, primary production, light and nutrients

As shown in Fig. 36a & b the nutrients NO_3 and PO_4 are used most efficiently, as it seems, at depths where concentrations are very low, and NO_3 the most. This is also reflected in the difference between c and d in Fig.


A
B
C
0
5
10
15
20
30
40
50
m depth
gcal/cm²/day
500-550 nm
1
2
3
4a
4b
4c
5
6
7
8
J
J
A
S
O
M
J

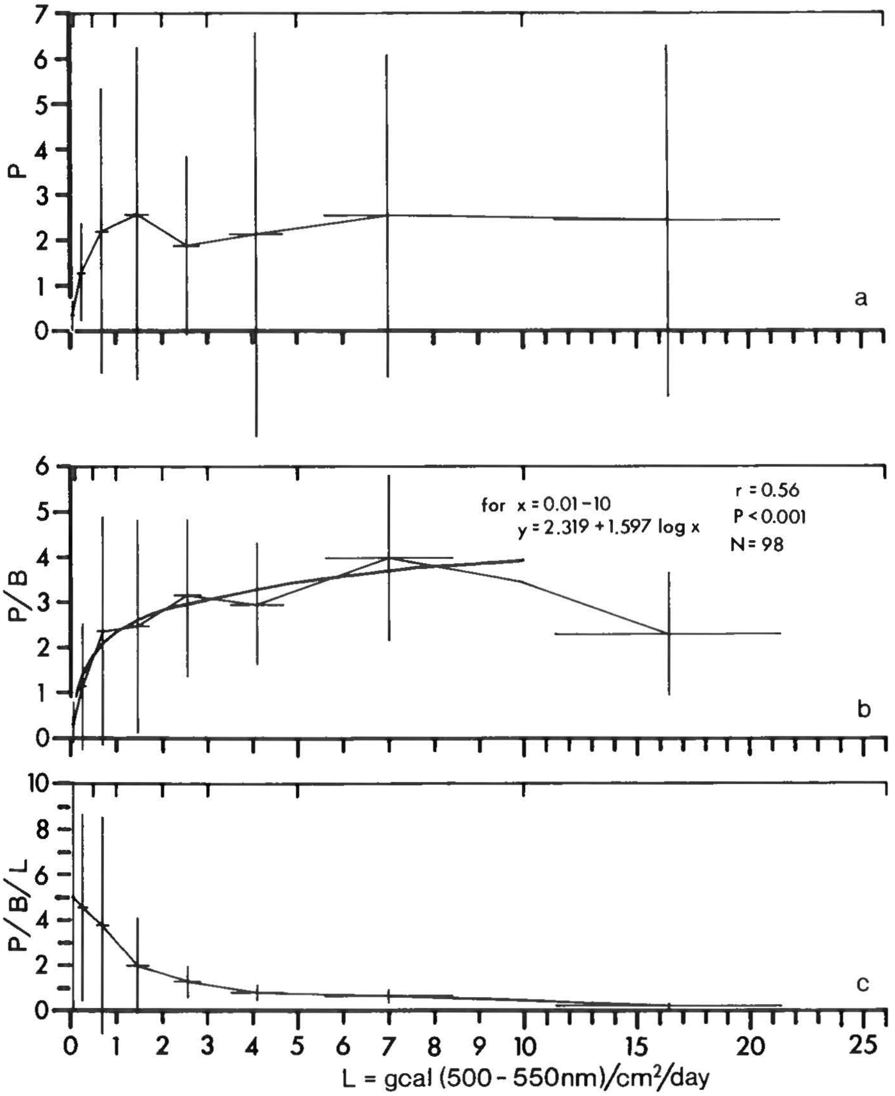


Fig. 33: Godhavn 1974 & 1975. In a, b, and c respectively, means of P, P/B, and P/B/L ± s.d. (verticals) cross means of L ± s.d. (horizontals). P = daily production = mg C/m^3; B = biomass = mg chlorophyll *a*/m^3; L = daily sum of green light (500–550 nm) = gcal/cm^2 – note change in scale at 10. Correlation between P/B and L. Light intervals and no. of data in each are as follows:

gcal/cm^2/day	0.01–0.1	0.1–0.5	0.5–1	1–2	2–3	3–5	5–10	10–26
N of P, P/B, & P/B/L	13	18	16	14	13	11	13	13

Fig. 32: Godhavn 1974 and 1975. A: Relative changes in P/B (mg C · day^{-1}/mg chl. *a*) compared to relative changes in daily light sum (gcal (500–550 nm) · cm^{-2}) and NO$_3$-N (µgat/liter). (1) Rel. change in P/B with depth ÷ rel. change in daily light sum > + 3%, due to drop in light inhibition with decreasing illumination and/or to adaptations in the algae to different light sums or illuminations. (2) As (1), but perhaps involving increasing concentrations of NO$_3$. (3) Rel. change in P/B with depth ÷ rel. change in daily light sum > + 3%, due to one or more of the 3 factors: Change in light inhibition, in adaptation to light sums or illuminations, and in concentrations of NO$_3$. (4) Rel. change in P/B with depth ÷ rel. change in daily light sum < + 3% at constant (a), increasing (b), and decreasing (c) concentrations of NO$_3$. (5) Probable lower limit of light inhibition. (6) Possible lower limit of light inhibition and/or of positive response to increasing concentrations of NO$_3$. (7) Lower limit of light measurements. B: As A, but with PO$_4$-P instead of NO$_3$-N. C: Upper: Daily sum of surface transmission of green light (500–550 nm). Lower: Combination of A and B. (8) Rel. change in P/B with depth ÷ rel. change in daily light sum < +3%.

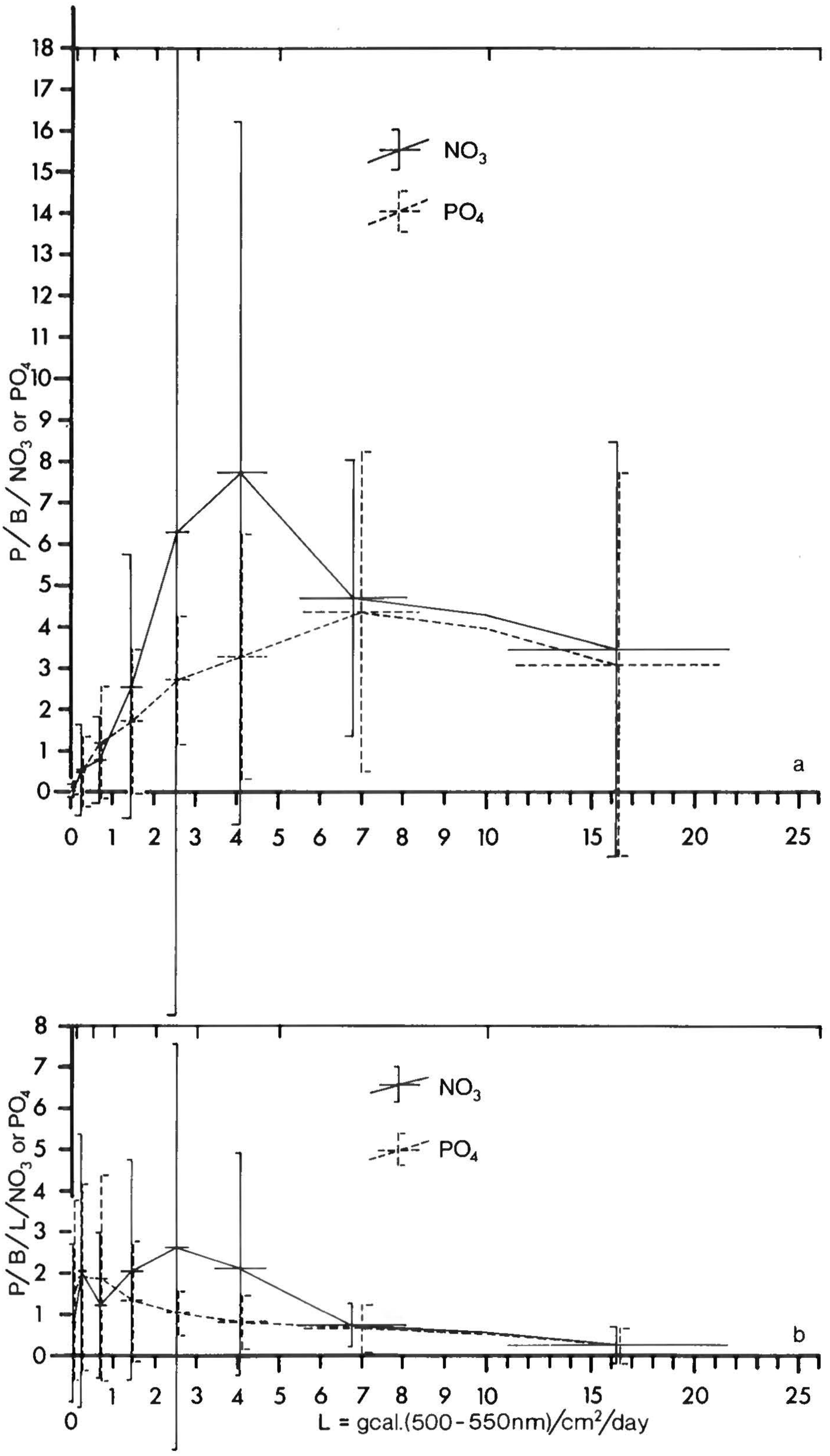


Fig. 34: As b and c in Fig. 33, but with the ordinate additionally divided by NO_3-N or PO_4-P (µgat/liter).

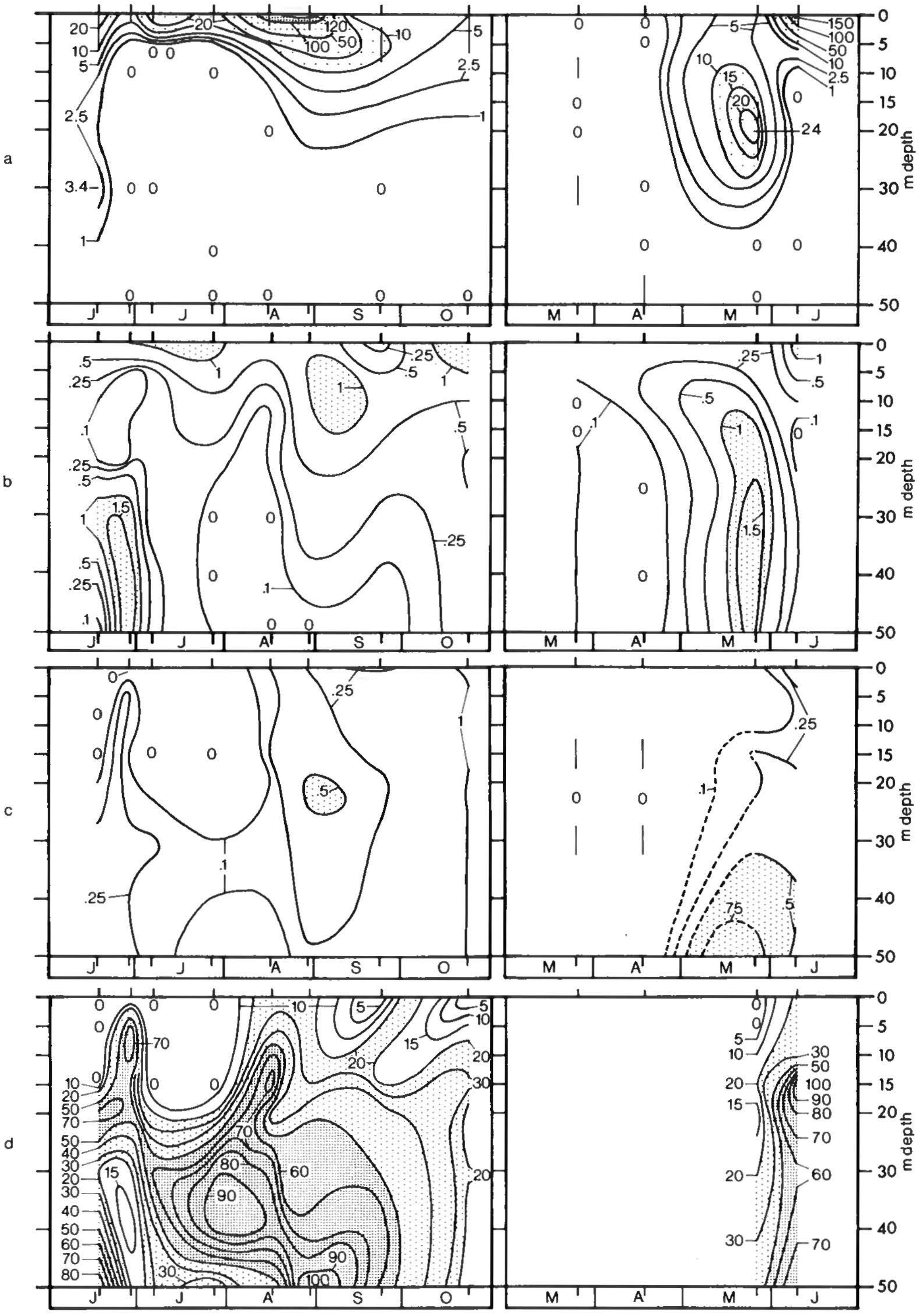


Fig. 54: Kangikerdlak 1974 (left) & 1975 (right). Isopleth diagrams of: a: Primary production (mg C/m^3/day); b: Chlorophyll *a* (mg/m^3); c: Phaeopigment (mg/m^3); d: $10^2 \cdot$ phaeopigment/(phaeopigment + chlorophyll *a*). Measurements made at depths indicated at the right and on dates marked below.

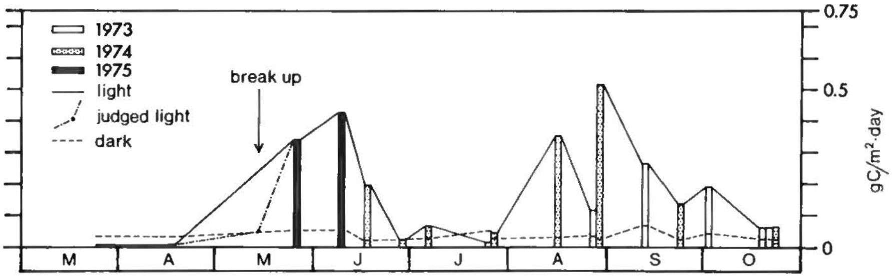


Fig. 51: Kangikerdlak 1973–75. Primary production (bars) and dark fixation of carbon (dashed curve) in the upper 50 m for each experiment (g C/m²/day). The full curve covers all experiments, the dotted-dashed curve is estimated from hydrographic data, and from measurements of production made at Godhavn.

Hydrography in other parts of the Disko Bugt area

In a previous paper (Andersen 1981) temperatures and salinities of the entire Disko Bugt area have been thoroughly dealt with. Only the limited data available on illumination, nutrients, O_2 and pH will be treated here according to areas shown in Fig. 56.

Illumination

Fig. 61 shows the only comparable series of light measurements from different parts of Disko Bugt. Attenuation is greatest off Atâ Sund and at Godhavn, but correlation to pigment concentration is low, only 0.45 because of great non phytoplankton turbidity, especially off Atâ Sund. At Christianshåb and Egedesminde, where attenuation is least, correlation is zero and negative respectively.

Nutrients

Depletion of phosphate in July in the surface layers, as a consequence of the spring bloom in the plankton, is most thorough, and reaches its greatest depth in the stabilized surface water off Godhavn and in the Vaigat as shown in Fig. 57A and B. In the more unstable water W of Egedesminde and in the S and E parts of the bay surface values do not reach the same low, whereas the PO_4-P content in the subsurface layers generally is lower here than beneath the freshened surface layers of areas W4, W1, G, B, and parts of area J and the Vaigat.

Four series from Aug. 1974 (Fig. 61) demonstrate the lowered PO_4-P content of the relatively well mixed water at Egedesminde and Christianshåb also extending to Godhavn beneath a more stabilized surface layer of 15–20 m, where the PO_4-P content is even lower. In the

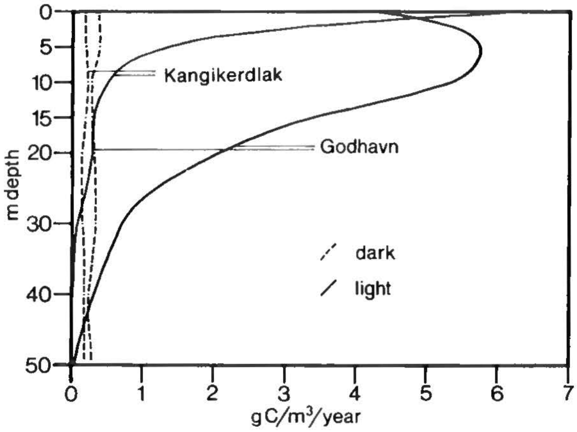


Fig. 52: Godhavn and Kangikerdlak 1973–75. Mean yearly profiles of primary production (light) and dark fixation in the upper 50 m.

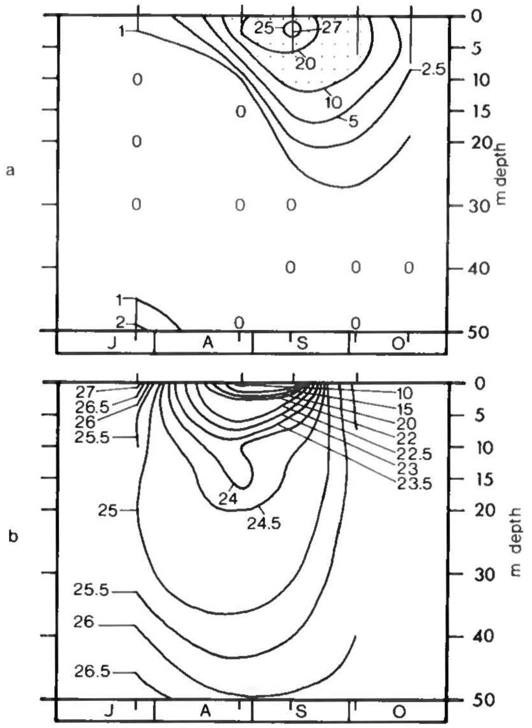


Fig. 53: Kangikerdlak 1973. Isopleth diagrams of: a: Primary production (mg C/m³/day); b: CO_2-C (mg/liter). Measurements at depths indicated at the right and on dates marked below.

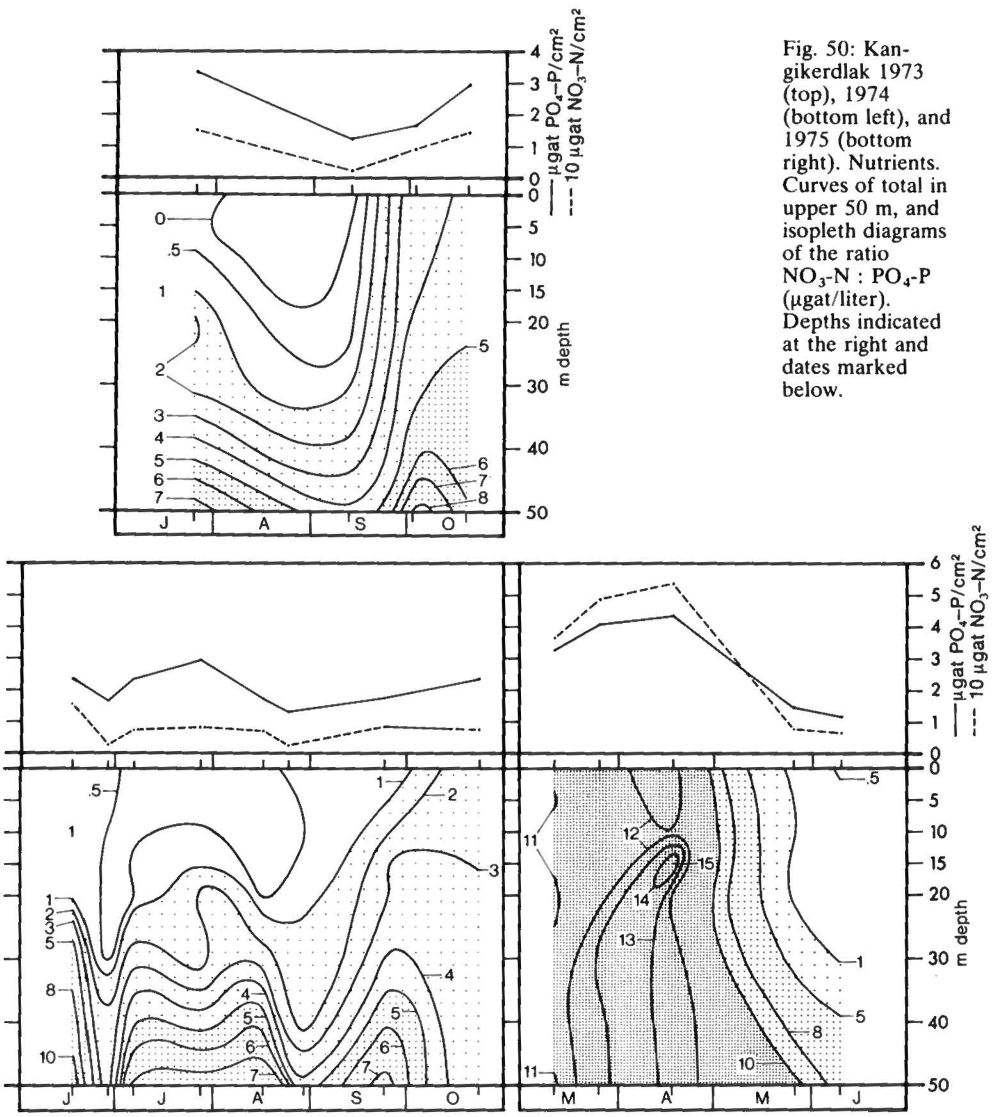


Fig. 50: Kangikerdlak 1973 (top), 1974 (bottom left), and 1975 (bottom right). Nutrients. Curves of total in upper 50 m, and isopleth diagrams of the ratio NO_3-N : PO_4-P (µgat/liter). Depths indicated at the right and dates marked below.

when the water clears, that production again goes deeper, though not deeper than about 20 m (Figs 53 & 54).

Phytoplankton pigments

In Kangikerdlak as at Godhavn chlorophyll *a* is found in greatest concentrations beneath the production maxima. This means that also here it is found in virtual darkness with the same exception in Aug., where it is concentrated in quite well illuminated water above 15 m (compare Figs 47 and 54). Concentrations are, however, very low, usually $^1/_{10}$ or less of those found at Godhavn, and the maxima reach only about $^1/_5$ of the corresponding maxima at Godhavn. Where illumination is less than 0.1% of surface transmission in late July through Sept., and of course before May, the amounts are unmeasurable with the technique used.

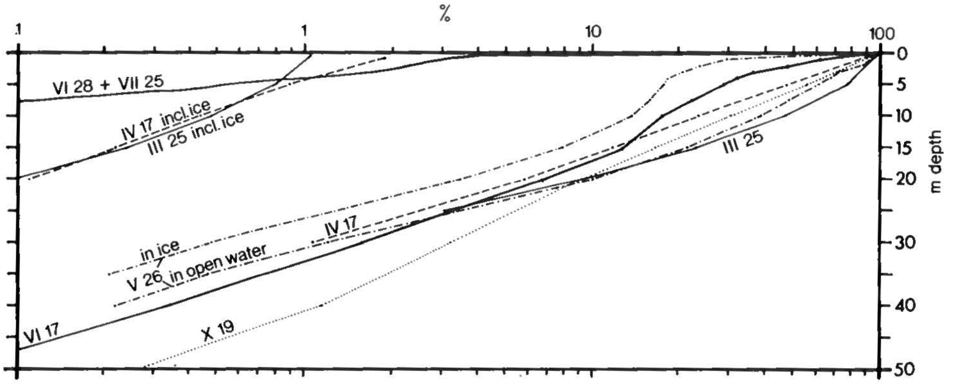
Phaeopigments are not quite as scarce, relatively, as chlorophyll *a*, but are often unmeasurable and reach only about $^1/_2$ to $^1/_3$ of the concentrations at Godhavn. So the calculations shown in Fig. 54d are not fully reliable.

The same applies to the chlorophylls *b* and *c*, the profiles of which also here are quite congruent to those of chlorophyll *a*. The relative abundance of the three seems to be roughly the same as at Godhavn – *a*:*b*:*c* = 10:2:5 – and the concentration of chlorophyll *a* fluctuates the most (Fig. 55).

Dark fixation

Dark fixation is fairly evenly distributed both in time and space, as at Godhavn, but the total is less than at Godhavn, amounting to only about 15 g C/m²/year (Figs 51 & 52).

Fig. 46: Kangikerdlak and Nångissat (on 26 May). Green light (500–550 nm) energy as percentage of surface transmission – most characteristic seasonal variations mentioned in the text.



light attenuation was measured a few metres below the surface, while the first measurements to be made on 10 Aug. show that the turbid layer here is very thin and dense, and is found at the immediate surface. There is a slight rise in the extinction coefficients in the lower thermocline at about 20–40 m, presumably caused by higher concentrations of both suspended material and plankton. Going out of the fjord, turbidity decreases and becomes more evenly distributed with depth (Fig. 48).

Nutrients

Nutrients clearly correlate to water masses during the winter, where the entering in Mar. – Apr. of saline water is associated with increasing concentrations of PO_4-P and NO_3-N, indicating an entire exchange of the water in the fjord. The concentration profiles of these two components are then completely congruent (Fig. 49), as is more or less the case below the euphotic zone during the summer, both here and at Godhavn,

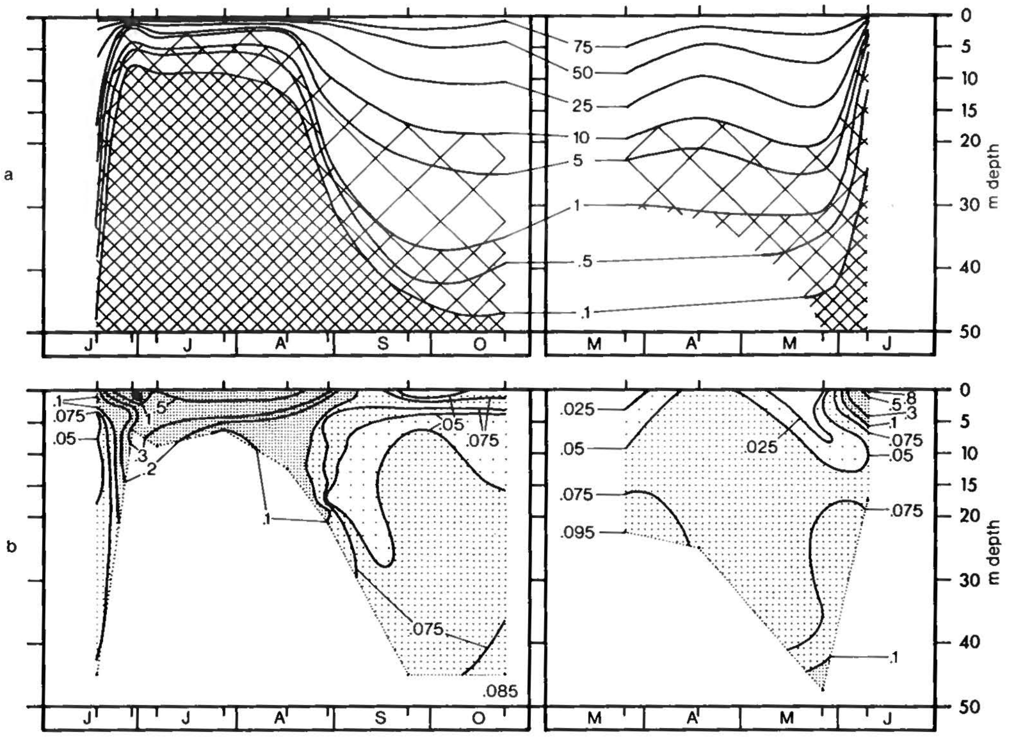


Fig. 47: Kangikerdlak 1974 & 1975. Isopleth diagrams of: a: Green light (500–550 nm) energy as percentage of total daily surface transmission. b: extinction coefficients (^{10}log basis). Measurements made at depths indicated at the right and on dates marked below.

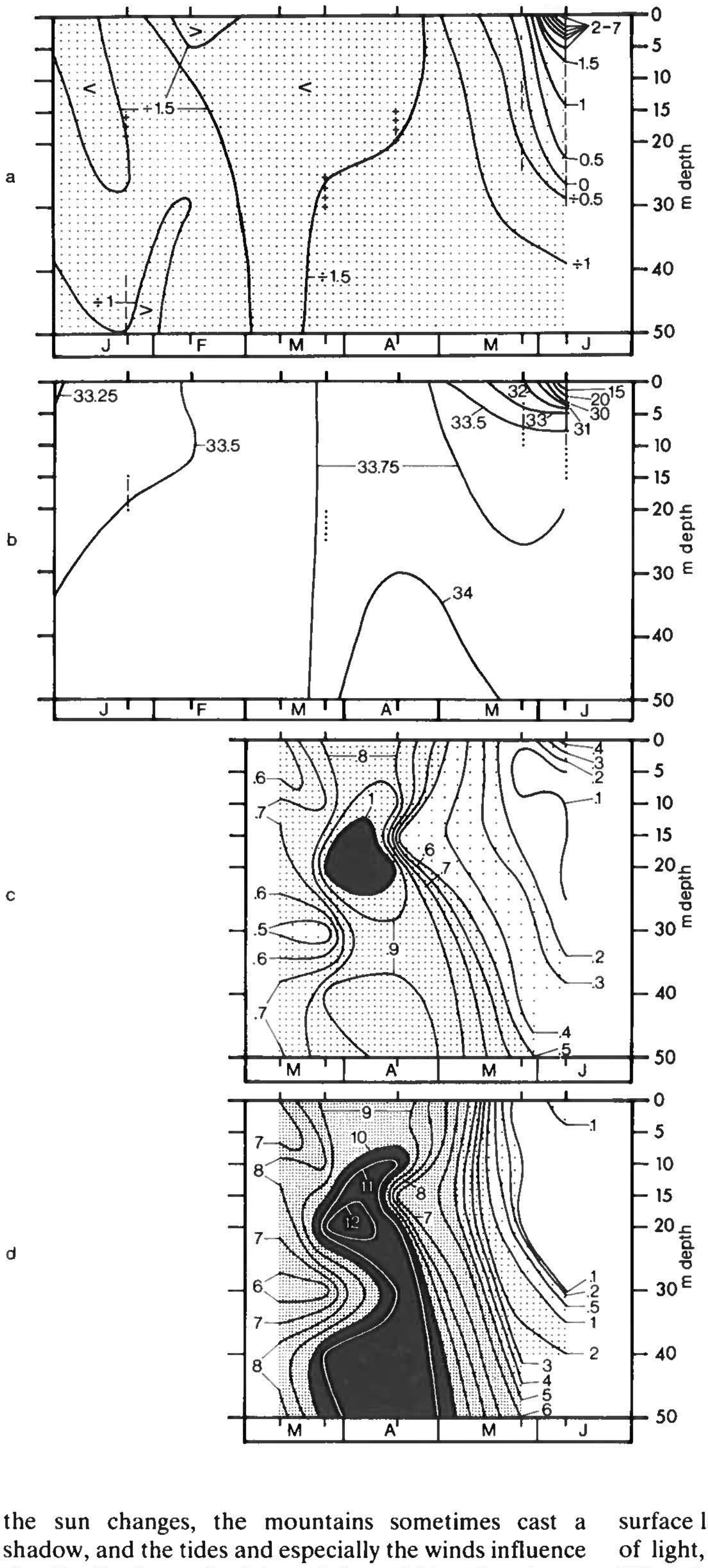
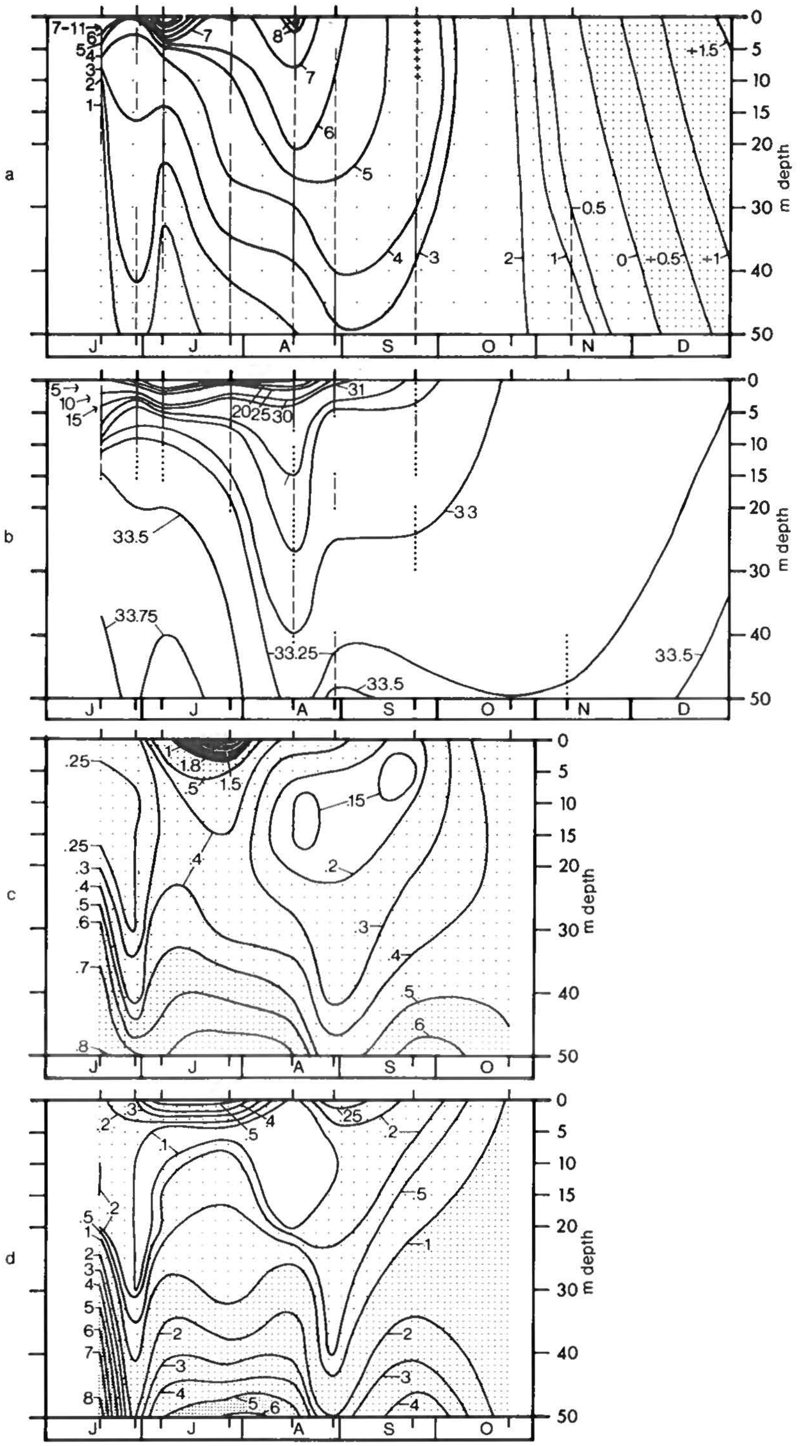


Fig. 45: Kangikerdlak 1975. As Fig. 44, except that the series on 26 May was at Nãngissat.

the sun changes, the mountains sometimes cast a shadow, and the tides and especially the winds influence the distribution and mixing of the turbid surface layer. Measurements of subsurface illumination made in Kangikerdlak (Fig. 48 a-c) show that the outflowing fresh surface layers are extremely turbid, limiting the amount of light, which is able to penetrate to deeper layers. Winds blowing into the fjord are able to hold back the turbid layer, whereas during calm weather it spreads out over the fjord. At 13:30 hrs on 9 Aug. a high degree of

Fig. 44: Kangikerdlak 1974. As Fig. 43, except that temperature and salinity was also measured at 0.5, 1, 2, 3, 4, and 7.5 m.



belt reaching the photo cell. A similar effect from thin turbid surface layers made light measurements difficult inside Kangikerdlak, especially in the spring, when wind and tides and the movements of the ship disturbed the surface layers (VI 17 in Fig. 46). Surface turbidity is greatest in late June and in most of July and Aug., diminishing again in Sept. (Fig. 47).

The light conditions below the surface in Kangikerdlak vary not only through the year, but also considerably in a 24 hour period, where the declination of

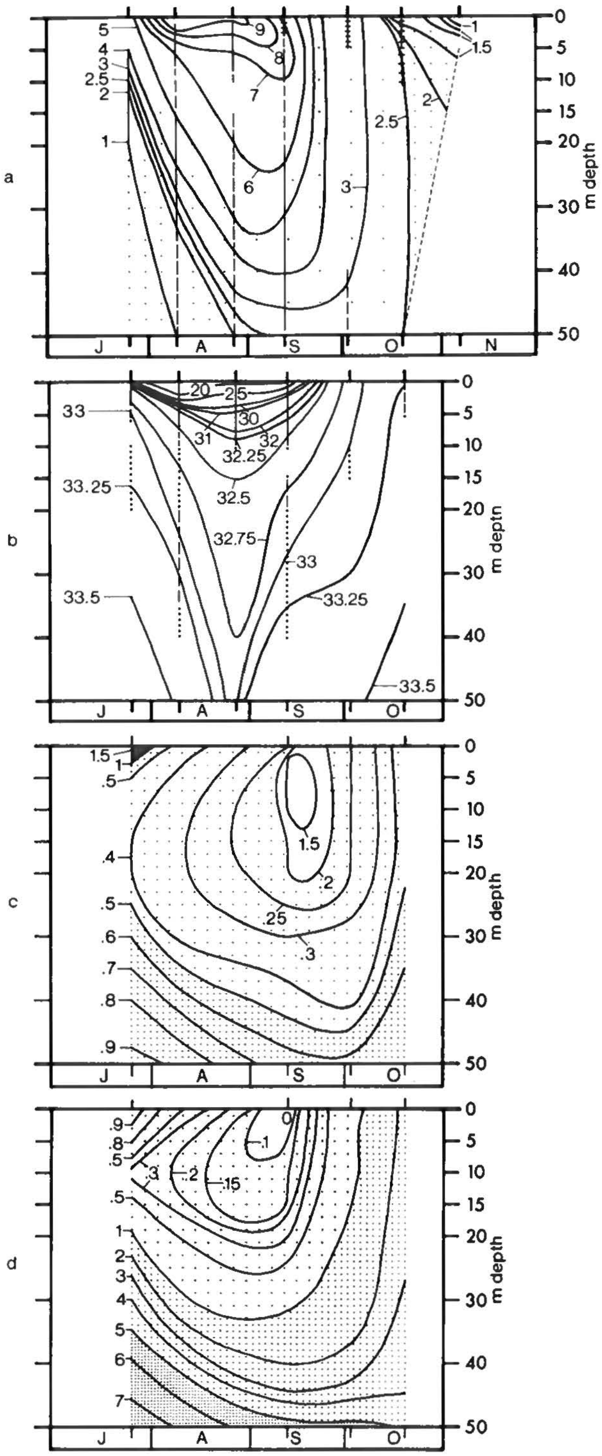


Fig. 43: Kangikerdlak 1973: Isopleth diagrams of: a: Temperature (°C), changes in temperature with depth are indicated as follows: Full vertical = ÷ 1°C/10 m, dashed vertical = ÷ 1°C/25 m, barred vertical = + °C/10 m, and crosses = + 1°C/25 m. b: Salinity (‰), changes in salinity with depth are indicated as follows: Full vertical = + 1‰/10 m, dashed vertical = + 1‰/25 m, and dotted vertical = + 1‰/50 m. c: PO_4-P (µgat/liter). d: NO_3-N (µgat/liter). Depths are indicated at the right and dates marked below.

Godhavn, while at greater depth the water remains colder. At 50 m the highest summer temperature is generally 0.5°C lower than at Godhavn and 2.8°C was the highest recorded as opposed to 3.3°C at Godhavn.

Deep intrusions of saltier water at Godhavn are not always registered in Kangikerdlak, presumably also because of the current – predominantly a surface current – flowing from Disko Bugt past and into Disko Fjord, especially in the summer and fall, and because of the shallowness of the fjord entrance and the shallow area SW of Disko. An upwelling of warm saline water off Godhavn in Oct. 1974 was accordingly not parallelled in Kangikerdlak. On the other hand, any warming and freshening in the upper 50 m at Godhavn can generally be detected some days later in Disko Fjord.

Surface cooling sets in in Aug., as off Godhavn, and vertical mixing is well under way by Sept.

The water movements in Kangikerdlak consist mainly of an outflow of fresh and diluted surface water counterbalanced by a deep inflow of saltier water. This process is subject to great fluctuations, as described by the author (1981), due to the changing tides and above all to powerful fjord winds which in their strongest form may sweep the surface layers swiftly out of the fjord arm drawing saltier water to the surface.

Illumination

In Disko Fjord light attenuation is greater than in the bay, even in winter, and non phytoplankton turbidity is the dominating factor, especially close to the surface. Here the extinction coefficients due to turbidity – excluding that caused by phytoplankton – are twice as high as the 0.2 proposed by Strickland (1958) for very turbid coastal water. Correlation between extinction coefficients and pigments at each depth is entirely lacking (Table 1). In May and early June, however, before surface turbidity has reached any appreciable magnitude, there is good correlation in the single series as on 26 May (Table 2), but as shown in Fig. 13c-e there is no true relationship between attenuation of light and pigment content.

In Kangikerdlak in the inner part of Disko Fjord the 1% depth varies from only 4 m in mid summer, when the outflow of fresh, turbid surface water is at its maximum, to about 40 m in Oct. Beneath the ice in Mar. and Apr. 1% depths of 1 m and 4.5 m respectively have been measured (Fig. 46). As shown in the same figure, the 1% depth was not at its greatest in Apr. and presumably not even in Mar., as one might expect from direct observation and from plankton tows. The reason for this is not known, but it cannot derive from a lower declination of the sun, and must be caused by the ice. On 26 May 1975 light was measured outside and about 50 m inside a belt of ice floes bordering the fast ice covering the fjord inside Nângissat at that time. A seemingly greater transparency found at 5–10 m beneath the ice floes is caused by light from outside the ice

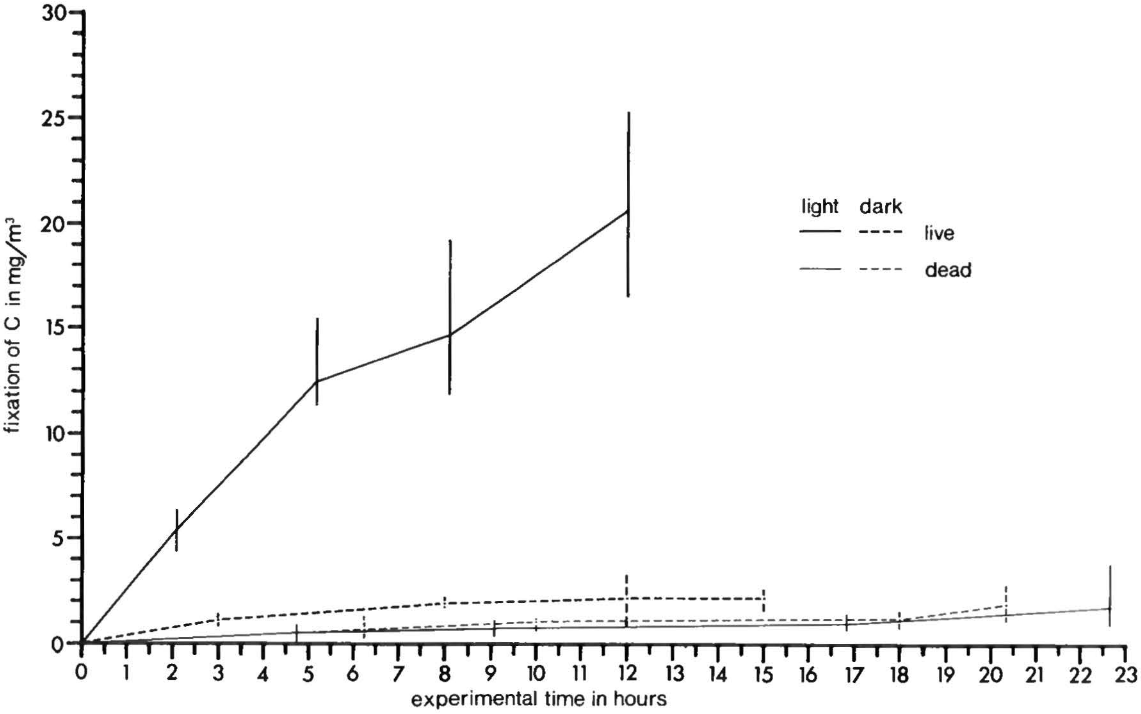


Fig. 42: Godhavn 1973. Carbon fixation (means of 5 experiments) is plotted against time for live and dead fixation in dark and in light. Light fixation = light bottle ÷ dark bottle interpolated to the time of filtration of the light bottle. Verticals connect highest and lowest of 5.

of primary production, from 9.87% to 5.80%. The continuous increase in the abiotic fraction possibly occurs at the expense of the biotically fixed CO_2, the proportion of which, after an initial rise to 64.7% after 5 hours, gradually falls to 51.6% after 15 hours. This comparatively large contingent of abiotic processes may, however, be an artifact caused by the killing of the organisms in the experimental bottles, whereby intracellular substances are released into the water, where they in the form of dead organic matter contribute significantly to the dark processes.

At Godhavn no correlation to the nutrients in general was found, but, as shown in Tables 5 and 6, there are examples of negative correlations between dark fixation and NO_2-N, NO_3-N, and PO_4-P which, however, must be a consequence of the positive correlations to chlorophylls and primary production. Nor is there any correlation to turbidity (measured as the degree of brown colouring of the C-14 filters). Dark fixation in the much more turbid waters in Kangikerdlak, in fact, is generally less than at Godhavn (Fig. 52). 16% to 64% (mean = 35.5% ± 14.3%) of dark fixation per m², however, is associated with particulate matter > 56 μ (Fig. 16) which presumably consists of organic matter, living or dead, and probably in part of phytoplankton, since there is some correlation ($r = 0.37$, $P = 0.10$) to the percentage of primary production by algae > 56 μ.

Hydrography of the upper 50 m in Kangikerdlak in Disko Fjord

Salinity and temperature

The isopleth diagrams for temperature and salinity in this small arm of Disko Fjord have the general seasonal aspects in common with the diagrams from Godhavn, but show less drastic short term changes (Figs 43–45).

The extensive winter cooling experienced off Godhavn is also found in Kangikerdlak, but conditions are not so uniform here, which is presumably caused by the many warm springs found in the Disko Fjord complex being active throughout the year (Fig. 45a & b). The warming from beneath caused by the West Greenland Current is also felt in Kangikerdlak, where – concurrent to events off Godhavn – slightly warmer and more saline water intrudes already in Mar. – Apr., raising surface salinities to above 33.75‰, while off Godhavn surface salinities remain lower than in Disko Fjord because of the current flowing out of Disko Bugt. In Kangikerdlak surface heating is slower and sets in later than at Godhavn, partly because of the more persistent cover of ice staying till well into May and because of the following greater stratification in the upper layers because of the outflow of fresh water. This more pronounced stratification, however, causes the maximum summer temperatures in the upper 40 m to be higher than at

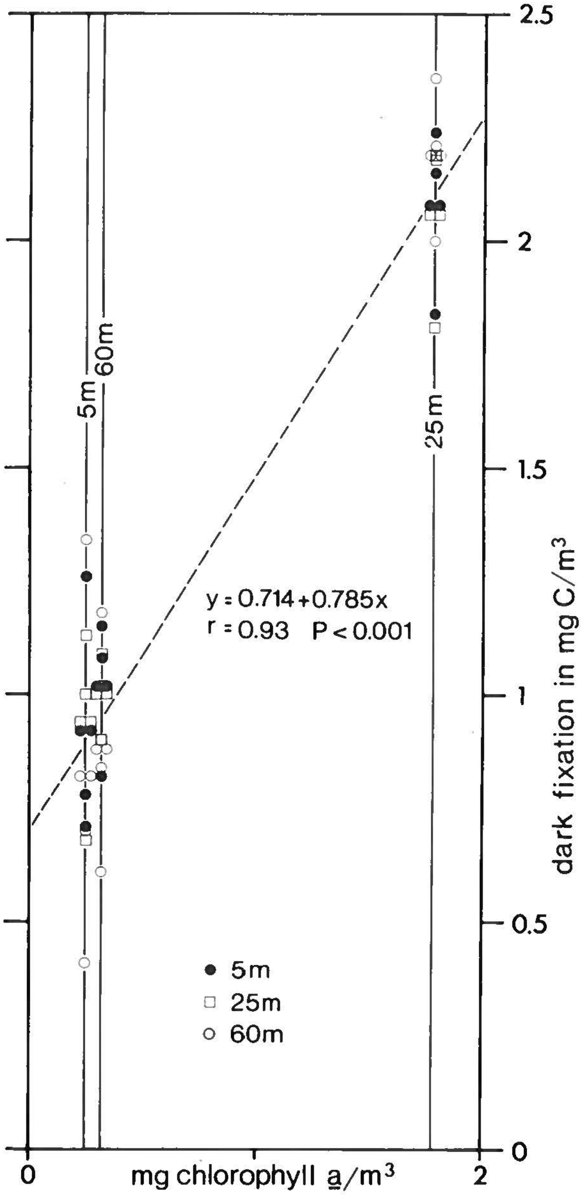


Fig. 41: Godhavn 1975. 27-bottle dark experiment. Dark fixation plotted against chlorophyll *a*. Depth of sampling (= depth of chlorophyll *a*), depth of exposure, regression line and equation, and correlation coefficient shown.

the highest light fixation rate of 168 mg C/m^3/day was measured.

It has no meaning, however, to correlate dark fixation with light fixation, except perhaps when production occurs under conditions of light saturation, as done by Steemann Nielsen (1960), and if it is assumed that production maxima indicate conditions of light saturation, as he has done, the production maxima/m^{3}day in 32 series from May to Oct. (1973–75) have corresponding dark fixations of 1.5% to 50% (mean = 9.44 ± 9.14%) of light fixation which is close to his mean of 8.5% for deep measurements around the Faroes, W of Ireland, and in Davis Strait. The variance is much higher, however, which is probably because light is less apt to be saturating at Godhavn.

Table 6: Correlation between dark fixation (y) and the x-correlates shown, in the dark experiments described in the text.

x-correlate	N	r	P
chl. *a*	27	0.93	<0.001
chl. *b*	27	0.93	<0.001
chl. *c*	27	0.93	<0.001
phaeopigm.	27	0.54	0.004
NO_2-N	27	÷0.60	0.001
NO_3-N	27	÷0.42	0.030
PO_4-P	27	÷0.37	0.065
total P	27	0.16	insign.

Table 7: Correlation between dark fixation (y) and the x-correlates shown, in all of the experiments from the series of 8 treated in Table 3.

x-correlate	N	r	P
light fix.	272	0.45	<0.001
chl. *a*	176	0.36	<0.001
alkalinity	63	÷0.34	<0.001

The 32 series mentioned have dark fixations per m^2 from 4.7% to 78% (mean = 19.1% ± 14.3%) of light fixation, whereas dark fixation far surpasses light fixation in Mar. and Nov. as shown in Fig. 16, as is also the case below the major productive zone as shown in Fig. 52. This, in principle, corresponds with Taguchi's & Platt's results from Bedford Basin.

The experiment, Fig. 42, seem to show that the dark fixation processes reach an equilibrium or saturation point after about 12 hours, under the given circumstances (10 m depth, 1.7–3.1°C, 32.2‰ sal.), and that half the saturation level is reached already after 3 hours.

A similar experiment performed simultaneously but with samples killed by adding formaldehyde to a concentration of 2%, however, shows that the dead – abiotic – portion of the dark processes does not reach a saturation point but continues to rise and even accelerates after 18 hours. The abiotic processes are not affected by light, and they are more closely correlated to light fixation than are the live(biotic)processes (r = 0.9653 compared to r = 0.9446, N = 4), and constitute 5.29% ± 0.99% of this. The biotic dark fixation – dark assimilation – may, however, as postulated by Taguchi and Platt (1977), more or less be based upon preexperimental light dependent processes, which can explain that they seem to reach saturation already after about 8 hours, after which the biotic fraction stays constant in absolute measure till the end of the experiment after 15 hours, and constitutes a smoothly falling percentage

Table 5: Correlation between dark fixation (y) and the x-correlates shown, in each series of 8 experimental depths (N = 8).

x-correlate	no. of series of 8	r for series of 8		r for series with significant r (P<0.05) arranged chronologically							
		variation	mean ± s.d.	29 VI 73	7 VIII 73	17 V 74	9 VII 74	18 VII 74	27 VIII 74	14 V 75	6 VI 75
light fix.	32	÷0.50–0.89	0.24±0.40				0.89	0.86			0.81
chl. *a*	23	÷0.48–0.77	0.09±0.38			0.77	0.73			0.72	
alkalinity	8	÷0.77–0.18	÷0.37±0.31		÷0.77						
NO_3-N	32	÷0.95–0.47	÷0.25±0.42				÷0.72	÷0.85	÷0.80	÷0.95	
PO_4-P	30	÷0.82–0.42	÷0.26±0.40	÷0.72			÷0.74		÷0.77	÷0.82	

centrations as low as 0.03 µgat/l had no effect upon P/B, whereas the possibility of some effect exists at concentrations from 0.02 to 0.26 µgat/l, but changes in light inhibition and perhaps more so in adaptations to low light intensities blur the situation here also.

Dark fixation

At Godhavn dark fixation in 227 days from 20 Mar. to 2 Nov., measured in 1973–75, is about 15 g C/m^2 or 66 mg C/m^2/day in the upper 50 metres. This is 16.4% of the annual primary production of 91.6 g C/m^2 calculated for the same period. As illustrated in Fig. 16 dark fixation is relatively constant throughout the entire period of primary production, and measurements of daily dark fixation vary between 8 and 116.6 mg C/m^2 with a mean of 61 mg C/m^2 ± 25.45 mg C/m^2 or ± 41.7% of the mean. The earliest and latest values are about 64 mg C/m^2 and 34 mg C/m^2 respectively, and assuming winter rates to be comparatively high due to higher nutrient levels (Platt & Irwin 1971) an estimate of 64 mg C/m^2/day for the remaining 138 days gives an annual total of about 24 g C/m^2 which is 26% of the light fixation.

If results of the 2–12 hour experiments dealt with below, showing that about 60–55% of dark fixation is biotic, are considered the rule, then this so called "dark assimilation" constitutes about 13–14.5 g C/m^2/year or about 14–16% of primary production. In absolute measure this is only about 25% of the 50 g C/m^2 annual dark assimilation found by Taguchi & Platt (1977) in the nutrient rich Bedford Basin, and only about half as much relative to primary production which was 200 g C/m^2 in Bedford Basin, or about twice that at Godhavn. Should, however, as mentioned below, dark fixation almost exclusively be biotic, then dark assimilation is about 25% of light fixation, as in Bedford Basin.

As shown in Fig. 52 dark fixation is fairly evenly distributed in the upper 50 m, corresponding to the results on dark assimilation in Bedford Basin found by Taguchi & Platt (1977). Their dark assimilation values showed close correlation to likewise evenly distributed microorganisms measured as ATP, and a partial correlation to primary production.

Dark fixation at Godhavn shows very little correlation to anything. In the standard series of 8 samples each (1973–75) there is no significant correlation ($P < 0.05$) between dark fixation and either temperature, salinity, pH, or phaeopigment, and there are only a few series where chlorophyll *a* (Fig. 40) and primary production are significantly positively correlated to dark fixation (Table 5).

A dark experiment using 27 samples, where 3 of 9 samples taken at each of 3 depths (5 m, 25 m and 60 m) were incubated at each of the 3 sampling depths, likewise showed no correlation between dark fixation and temperature or salinity, whereas dark fixation was closely correlated to chlorophyll *a* (Figs 40 & 41) as well as to chlorophylls *b* and *c* and to a lesser degree to phaeopigments (Table 6).

In spite of this there is in all standard series experiments from Godhavn (1973–75) only a minor significant positive correlation between dark fixation and chlorophyll *a* (Table 7).

In the dark/light experiments referred to above, four sets of 5 light + 5 dark bottles each were filled, injected with C-14 and exposed at noon and retrieved one set at a time after about 2, 5, 8 and 12 hours respectively (Fig. 42). The primary production values shown in the figure were found by subtracting the dark fixation values corresponding to the time of filtration of the light bottles and found with the aid of the dark fixation curve. In spite of a very close positive correlation ($r = 0.9758$, $P < 0.001$) between the dark fixation means and the primary production means, this does not indicate any causal connection between the two, since any rate of production, large or small, would give a curve of much the same appearance and just as well correlated to the dark fixation curve. Smoothing the production curve in Fig. 42, in fact, gives an r of 0.9992, whereas calculations on the basis of the single experiments yield correlation coefficients from an insignificant 0.33 ($P = 0.16$) to 0.81 ($P < 0.001$) depending on the pairing of light and dark experiments.

There is accordingly, just as the case is with chlorophyll *a*, only a partial – though greater – significant positive correlation between dark fixation and primary production in all of the standard series experiments treated together (Table 7), and this in spite of the fact that the highest dark fixation value of 4.14 mg C/m^3/day occurred on 7 May 1975 at 5 m where also

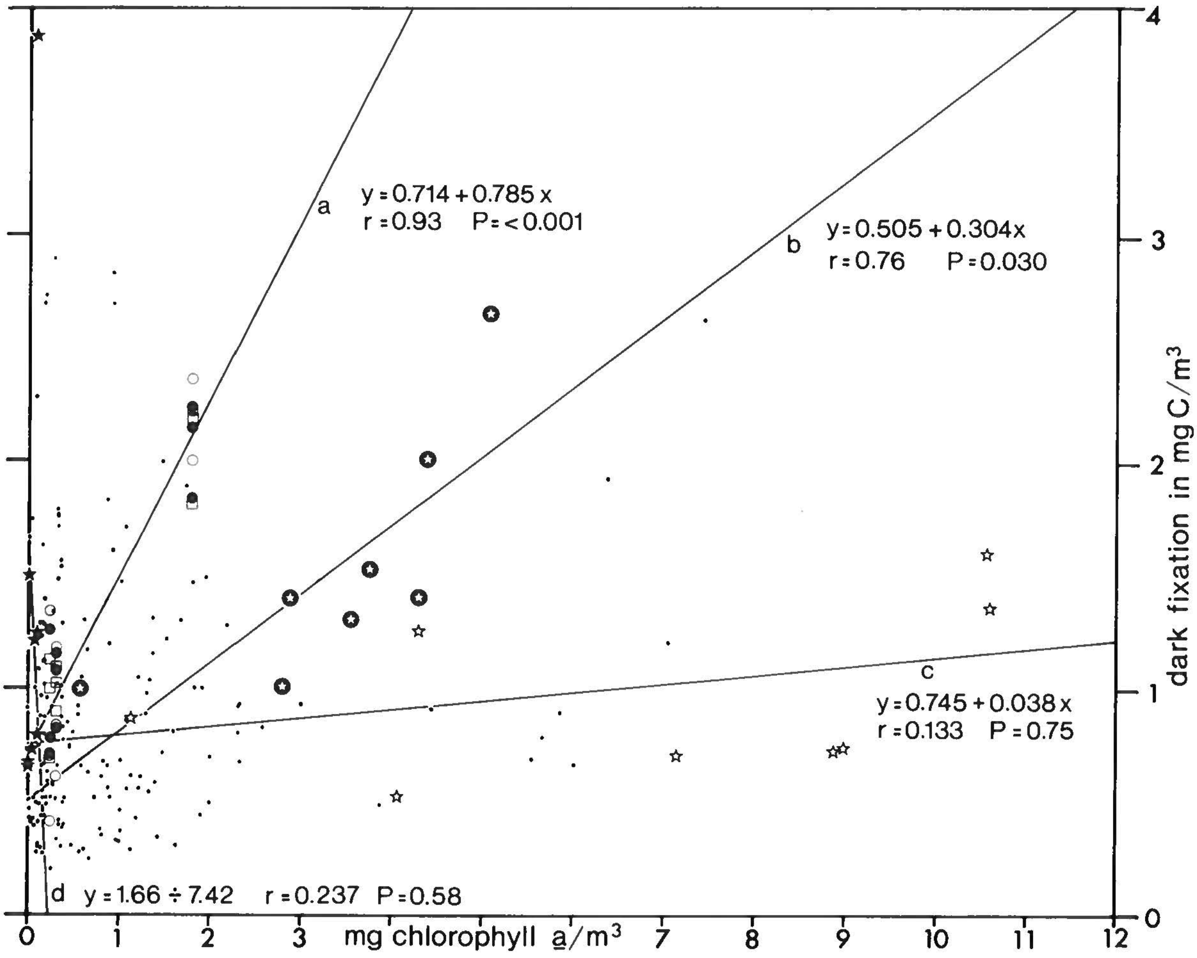


Fig. 40: Godhavn 1974 & 1975. Dark fixation is plotted against chlorophyll *a* for all standard series production experiments and for the 27-bottle dark experiment. Regression lines, equations and correlation coefficients are shown for the dark experiment (a), and for the three series of 8 production experiments showing the highest degree of correlation.

These high figures are presumably due to a reduction in light inhibition with depth (at 5–20 m and mainly at 5–10 m), and saturation levels for NO_3-N must be considerably lower than the highest concentration of 0.75 μgat/l (0.06–0.75, mean of means = 0.23 ± 0.22). This also follows from the fact that the NO_3-N concentration was below 0.75 μgat/l (0.01–0.75) in 11 of the remaining 24 cases as well, where the relative change in NO_3 was greatest (ordinates < 1 in Fig. 39 left), indicating some degree of saturation. Thus in some cases NO_3-N is at least partly saturating at 0.06 μgat/l and even at 0.01 μgat/l.

These figures resemble the peak efficiency levels (0.01–1.76 μgat/l) found in the P/B/L/NO_3-N correlations and the mean saturation level of about 0.35 μgat/l found in the P/B/L correlations. Similarly from the compilation of Fig. 32A, it was found that rising concentrations of NO_3-N from concentrations as low as 0.01 μgat/l had no effect at all upon P/B, whereas the possibility of some effect exists at concentrations from 0.01 to 0.67 μgat/l, but changes in light inhibition and/or adaptations to low light intensities blur the situation immensely.

Comparisons of the relative changes with depth between P/B, daily light sum and PO_4-P, as done for NO_3 in Fig. 39 right, show that saturation might be expected at concentrations well below 0.24 μgat/l (ordinates > 1 in Fig. 39 left represent concentrations of 0.1–0.24 μgat/l with a mean of means = 0.16 ± 0.03) at 0–40 m and mainly at 15–30 m, and at least partial saturation is evident at concentrations as low as 0.02 μgat/l (ordinates < 1 in Fig. 39 right).

These figures resemble the peak efficiency levels (0.02–0.50 μgat/l) found in the P/B/L/PO_4-P correlations somewhat, as well as the mean saturation level of approximately 0.24 μgat/l found in the P/B/L correlations. Similarly from the compilation of Fig. 32b, it was found that rising concentrations of PO_4-P from conappearing maximum of P/B/PO_4-P at 7 gcal/cm^2/day gives no clue, as to NO_3-N deficiency which is discernible from the supposed light inhibition effect shown in Fig. 33b, whereas the maximum of P/B/NO_3-N at 4 gcal/cm^2/day indicates that PO_4-P is liable to be limiting at concentrations below 0.17 μgat/l.

The more or less pronounced P/B maxima (Fig. 28, a & c) of 11.7 – 99.3 mg C/mg chl. *a*/day – one or two on each date at 0–30 m (mean = 9.46 m ± 9.06 m) – occurred at concentrations of NO_3-N which were more variable (0.00 – 1.80 μgat/l, mean = 0.34 ± 0.50 μgat/l) than those of PO_4-P (0.02–0.47 μgat/l, mean = 0.17 ± 0.10 μgat/l). Also the relationship between P/B and NO_3-N shown in Fig. 37 is very diffuse, although there is a definite drop in P/B (as in P mentioned earlier) at concentrations above about 1 μgat/l due to low illumination. There is, on the other hand, a fairly distinct (though statistically insignificant) rise in P/B with rising concentrations of PO_4-P to a maximum at about 0.15 μgat/l, after which efficiency drops – presumably due to a corresponding drop in illumination. Notable is, however, the high P/B (above average) even at the lowest (< 0.03 μgat/l) concentrations of both NO_3-N and PO_4-P.

The efficiency of production expressed as P/B/L does – when correlated with NO_3-N – seem to show that saturation in a number of series is reached with concentrations of 0.08–0.78 μgat/l, while there is a general though statistically insignificant increase with increasing concentrations to about 0.35 μgat/l (Fig. 37c). The lowest efficiencies, however, occur at 0.1–0.2 μgat/l – low values are even found at close to 2 μgat/l due to light inhibition – and efficiencies well above average occur when NO_3-N concentrations are below 0.005 μgat/l. In fact, at concentrations of NO_3-N below about 0.1 μgat/l, a rise in P/B/L with rising concentrations of NO_3-N only occurs, when there is also a rise in the concentration of PO_4-P which is from 0.02 to means of 0.06–0.17 μgat/l.

Only a few series show any regular relationship between P/B/L and the concentration of PO_4-P, reaching maximum effect at 0.17–0.22 μgat/l. All series treated together (Fig. 37c), P/B/L shows a definite, though statistically insignificant increase with rising concentrations of PO_4-P to about 0.24 μgat/l, after which there is an indefinite decline. The lowest efficiencies occur at less than 0.12 μgat/l, but even at 0.4 μgat/l very low efficiencies occur due to light inhibition at the surface.

Furthermore, the efficiency of production expressed as P/B/L/NO_3-N (Fig. 38b) shows a definite increase with falling concentrations of NO_3 down to the lowest values measured, with no evidence of concentrations being limiting to production. A number of the series, however, show definite peak efficiency rates at a variety of NO_3-N concentrations from 0.01 to 1.76 μgat/l with a mean of 0.36 ± 0.58 μgat/l, some of which may depict actual saturation levels.

Peak efficiency rates of P/B/L/PO_4-P in single series are reached at concentrations from 0.02 to 0.50 μgat/l with a mean of 0.20 ± 0.13 μgat/l, but unlike the case with NO_3, the highest efficiencies are not reached at the lowest concentrations, but at about 0.15–0.35 μgat/l, and the mean values reach a peak at about 0.24 μgat/l which may be the approximate mean saturation level under the given circumstances.

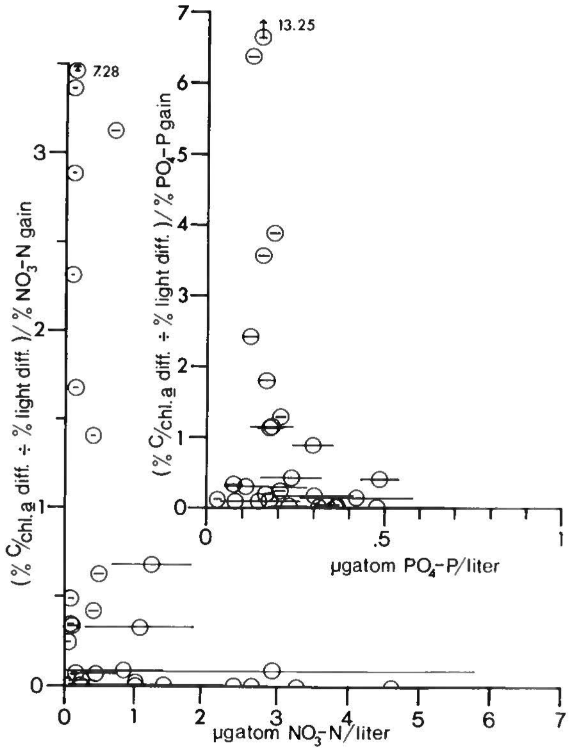


Fig. 39: Godhavn 1974 & 1975. Left: Efficiency gain with depth relative to light, expressed as relative change in daily P/B (% C/chl. *a* diff.) minus relative change in daily light sum, L (% light diff.) per relative gain in NO_3-N, is plotted against NO_3-N (μgat/liter), in 29 cases when both efficiency gain relative to light and change in NO_3-N concentration is positive. Horizontal lines denote each change and circles the corresponding means in NO_3-N concentration. Right: As left, but with PO_4-P instead of NO_3-N.

The phenomenon of light inhibition presumably causes much of the great variability in the various measures for efficiency of production. Comparisons of the relative changes with depth between P/B, daily light sum and NO_3-N give only limited information as to the saturation, partial saturation and deficiency levels of NO_3-N concentrations. In Fig. 39 left are plotted the 31 out of the 68 cases in 1974 and 1975 with changing concentrations of NO_3-N, where the relative change in P/B minus the relative change in daily light sum, as well as the relative change in NO_3-N were both positive. In 7 of these only, the relative change in P/B minus the relative change in daily light sum was the greatest (ordinates > 1 in Fig. 39 left), but this by as much as 7.28 times.

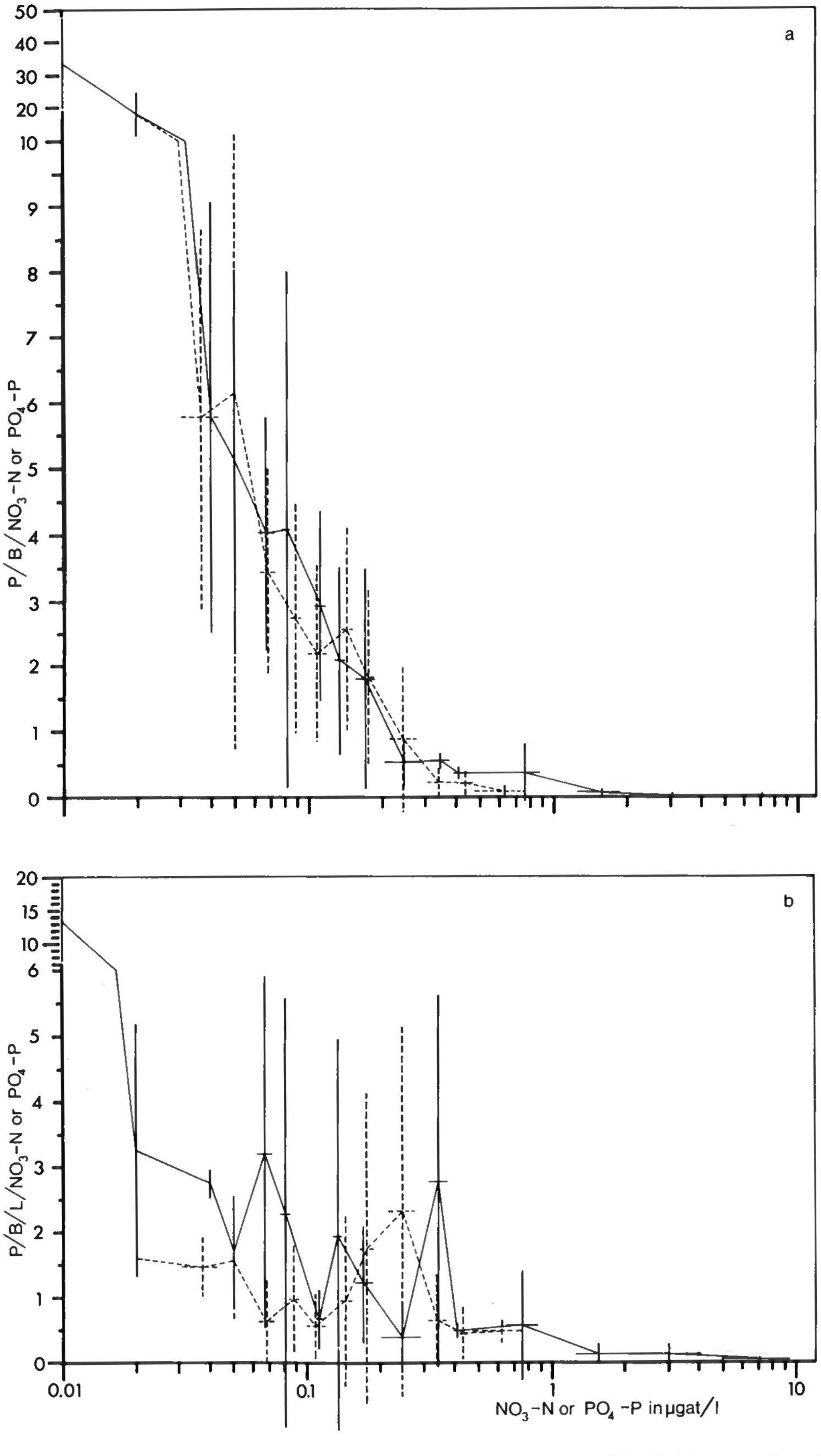
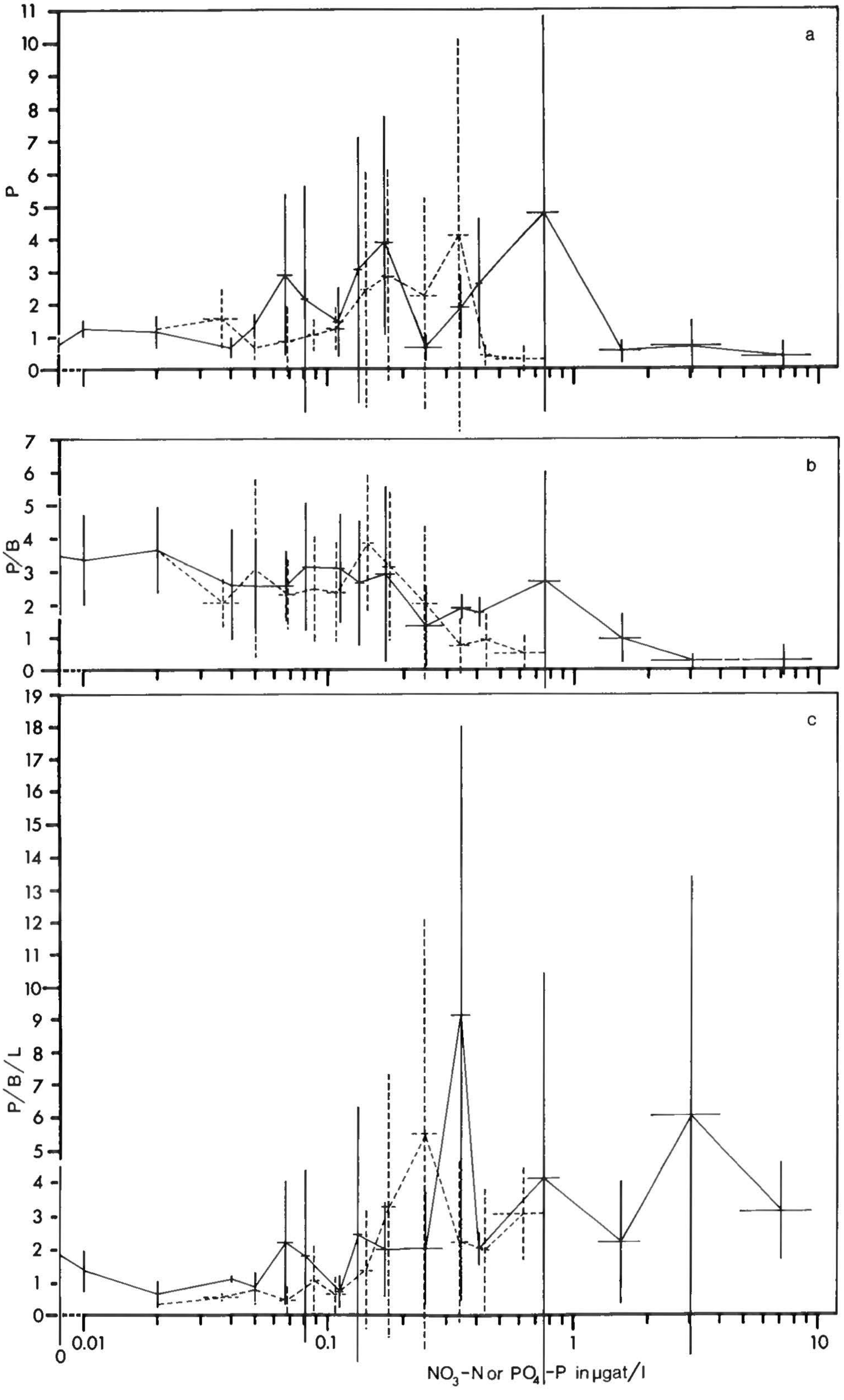


Fig. 38: As b and c in Fig. 37, but with the ordinate additionally divided by NO_3-N (–) or PO_4-P (– –) (µgat/ liter). Note change of scale in ordinate.


a
b
c
P
P/B
P/B/L
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
0
0.01
0.1
1
10
NO$_3$-N or PO$_4$-P in µgat/l

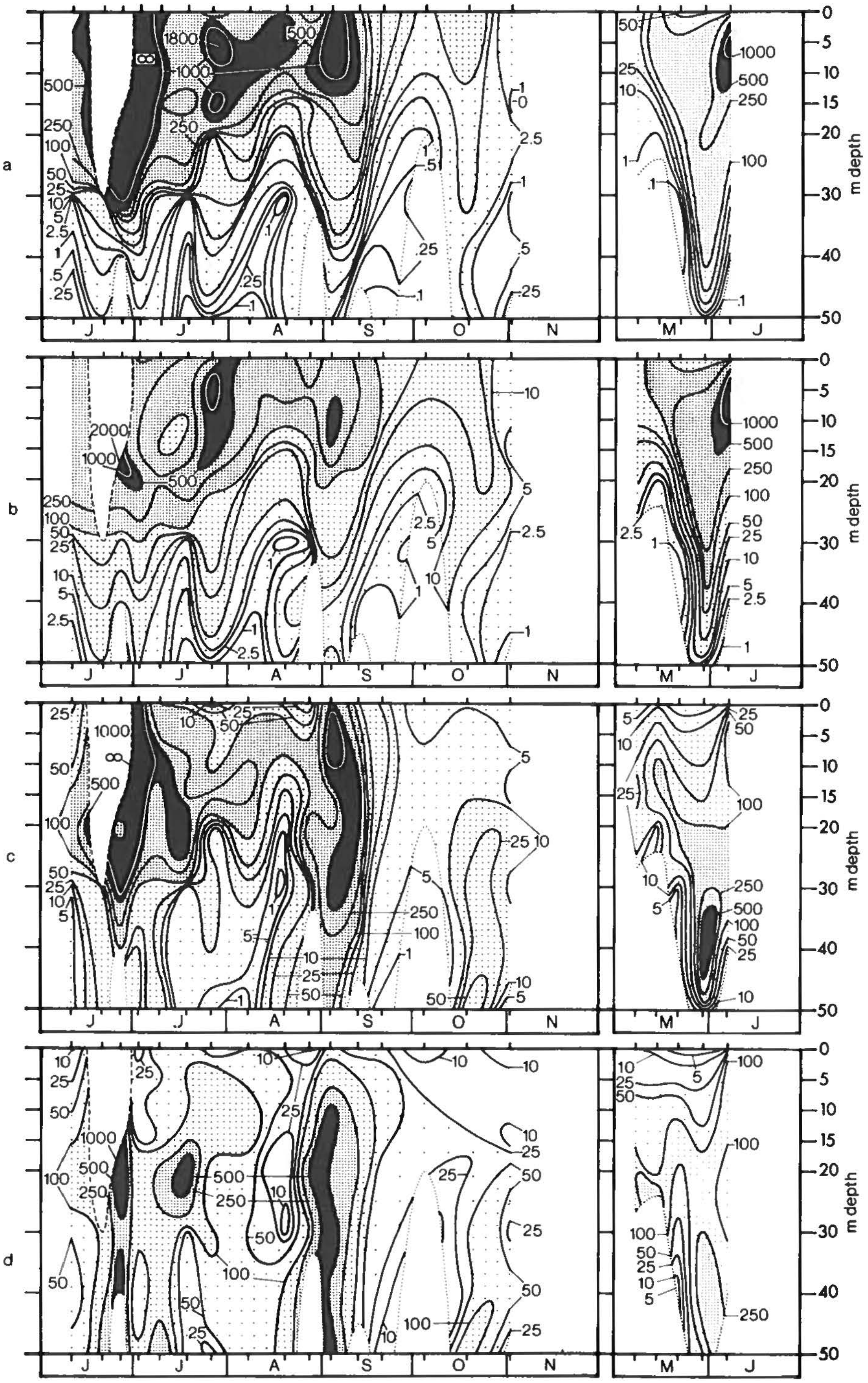


Fig. 36: Godhavn 1974 (left) and 1975 (right). Isopleth diagrams of: a: NO_3-N utilization expressed as $P/B/NO_3$ = mg C · day^{-1}/mg chl. *a*/mgat NO_3-N; b: As a, but for PO_4-P; c: NO_3-N and light utilization expressed as $P/B/NO_3/L$ = $P/B/NO_3$/gcal · cm^{-2} · day^{-1} (green light of 500–550 nm); d: As c, but with PO_4-P instead of NO_3-N. Dashed lines enclose pigment measurements and dotted lines enclose light measurements of less than the uncertainty on the instruments. Depths are indicated at the right and dates marked below.

Fig. 37: Godhavn 1974 & 1975. In a, b, and c respectively, means of P, P/B, and P/B/L ± s.d. (verticals) cross means ± s.d. of NO_3-N (–) and PO_4-P (– –) concentrations (µgat/liter) (horizontals). P = daily production = mg C/m^3; B = biomass = mg chl. *a*/m^3; L = daily sum of green light (500–550 nm) = gcal/cm^2. Concentration intervals and no. of data from each as in Fig. 27.

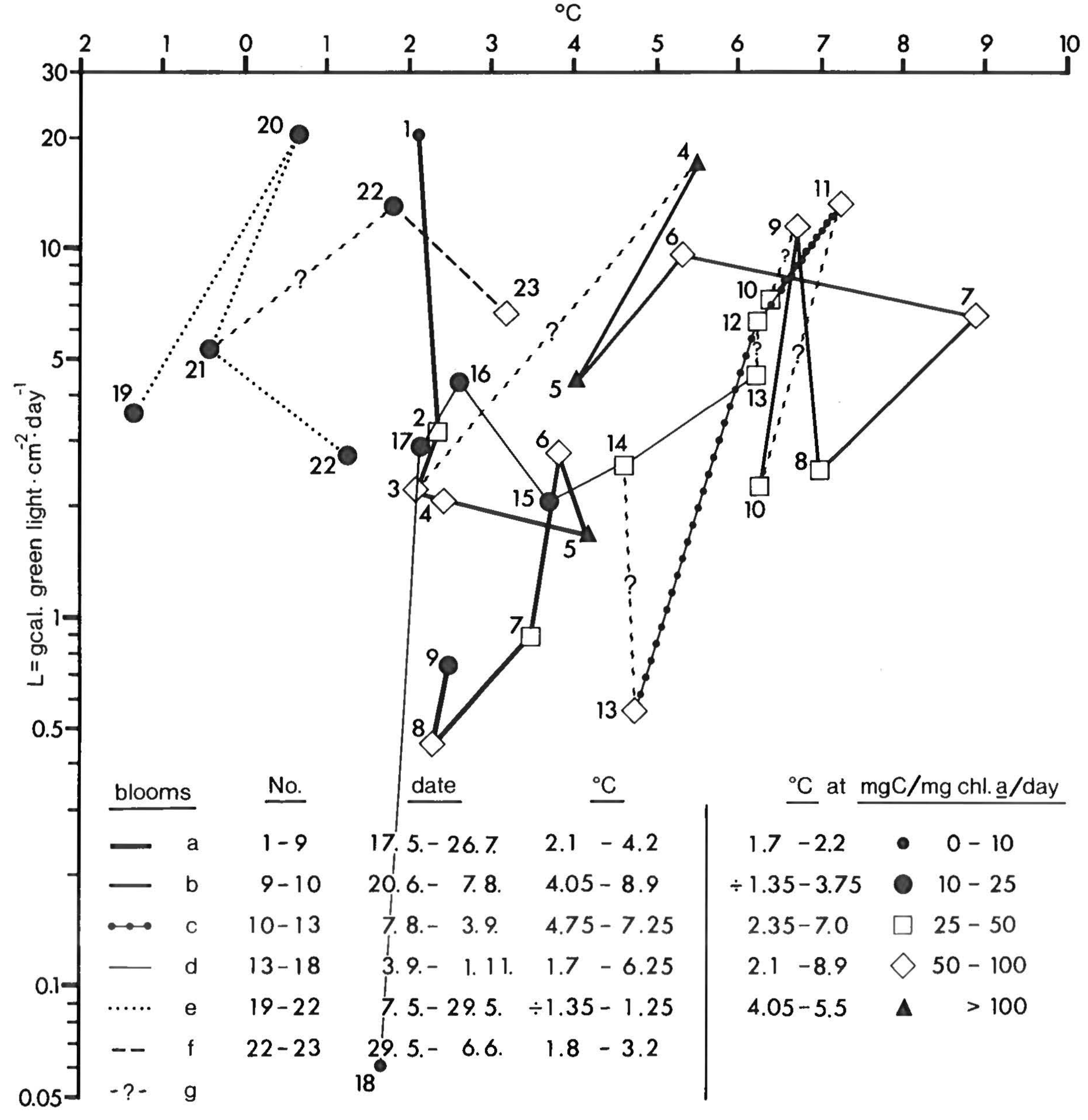


Fig. 35: Godhavn 1974 and 1975. Daily P/B maxima (mg C · day^{-1}/mg chl. *a*) plotted according to temperature (°C) and L = daily sum of green light (500–550 nm) (gcal./cm^2/day), and numbered chronologically. Maxima of populations believed to be of common origin are interconnected by like lines (a–f). Dates and nos of these "populations", and the corresponding temperature intervals as well as those of the P/B size categories are shown.

36, and in Fig. 14. It follows that a general correlation between primary production and nutrient concentration cannot be made. This is in part because – as it is best known from tropical seas – nutrients are utilized as soon as they are made available – if there is light and of course phytoplankton enough. Production is in fact, if anything, correlated negatively rather than positively to nutrient supply, since a reduction in nutrient content is a direct consequence of production.

Nor is production efficiency (P/B) correlated to nutrients, not even if the data, in an attempt to eliminate the effect of light inhibition and adaptations, are grouped according to the intervals of daily light sums used in Fig. 33. Curves of the interval means of P/B/NO_3-N and P/B/PO_4-P (Fig. 34a) should, if there is no deficiency in the (any) other nutrient, and no light inhibition, rise abruptly with rising light energy, as they do, and then gradually level off, which they do not. The

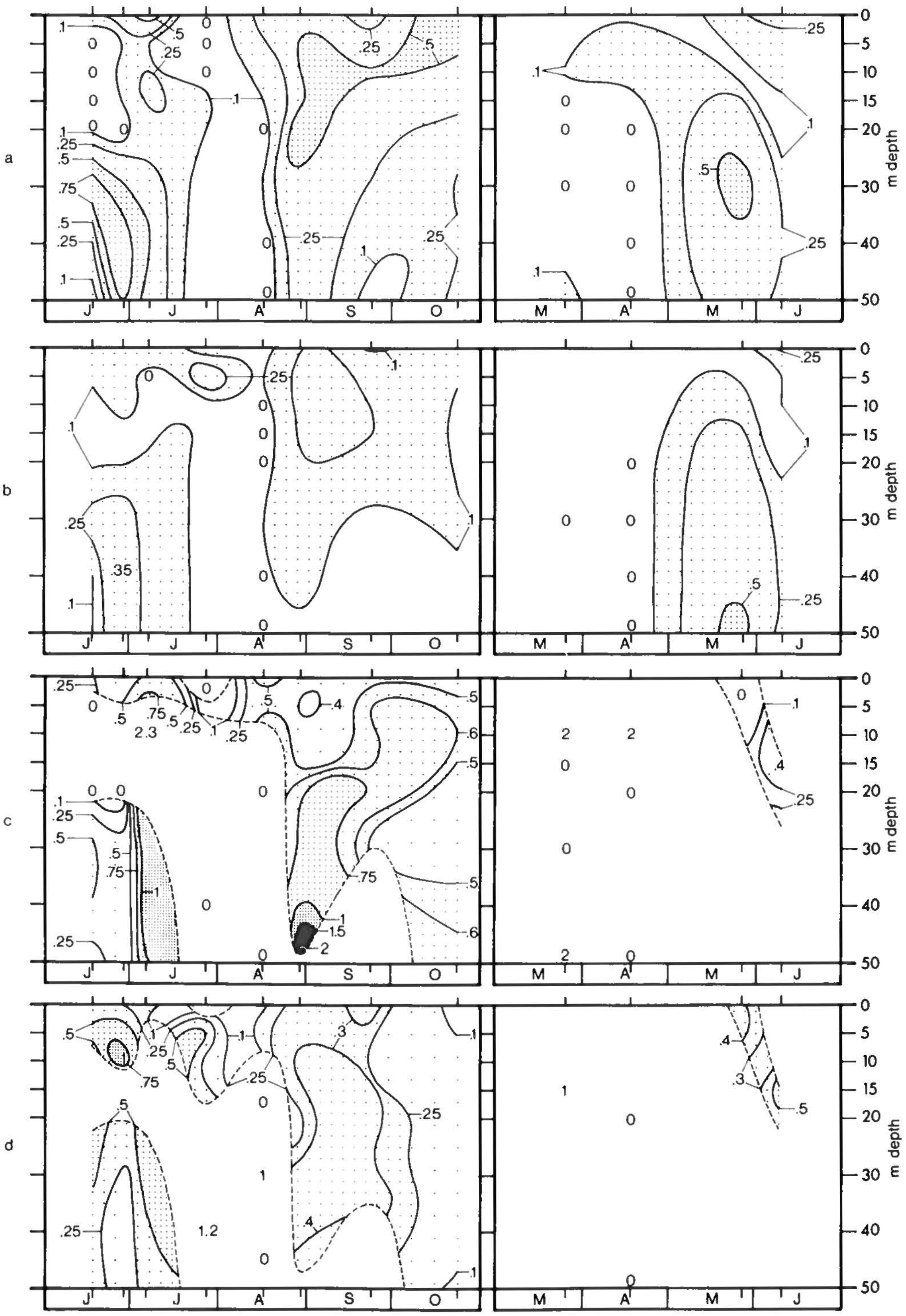


Fig. 55: Kangikerdlak 1974 (left) & 1975 (right). Isopleth diagrams of: a: Chlorophyll *c* (mg/m^3); b: Chlorophyll *b* (mg/m^3); c: Chlorophyll *c*/chlorophyll *a*; d: Chlorophyll *b*/chlorophyll *a*. Measurements made at depths indicated at the right and on dates marked below. In c and d only measurements greater than the uncertainty on the instruments have been used.

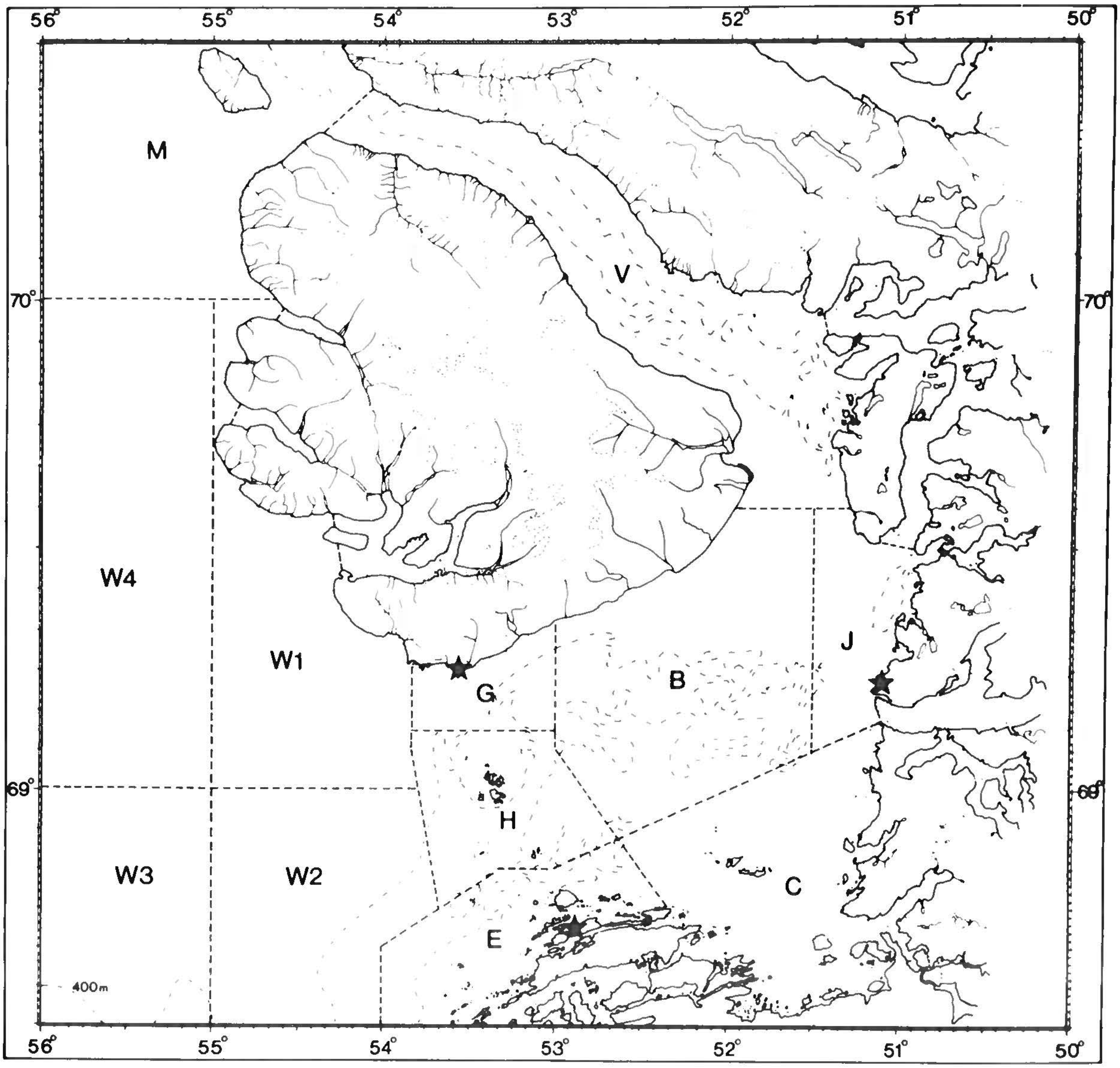


Fig. 56: Map of hydrographic regions in Disko Bugt and adjacent waters, as treated in the text, and in Figs 57 to 60.

NE part of area J, off Atâ Sund, depletion is marked in a very thin freshened and warmed surface layer only 4–5 m thick, below which an upwelling of mixed relatively warm water – compared to that found off Jakobshavn Isfjord – contains large amounts of PO_4-P. A maximum at 30–40 m seems traceable in a reduced form at Godhavn. (Fig. 57C).

By Sept. surface cooling and mixing again affords some replenishment of nutrients to the surface layers, already started in Aug. (Fig. 57D).

Very few data on NO_3-N content (Fig. 58) are available from areas other than area G, and those from 1928 (Hagen 1936) cover the surface and very few other depths only, and they were regarded as being rather uncertain and probably too low, by Hagen himself. A condition of complete depletion at the surface, however, seems to exist from July to Sept. Only one series from the W end of the Vaigat shows a condition of mixing and surface replenishment in Sept.

Otherwise almost complete depletion exists in the upper 20–30 m at Godhavn, and in the Vaigat, and even at Egedesminde and Christianshåb very low values are reached in the upper 15–30 m in Aug. Off Atâ Sund depletion is complete in the upper 5 m in Aug., whereas the NO_3-N content is very high only a few metres below this, in the cool halocline existing there, especially at 30–40 m. Also at Godhavn there is in Aug. a NO_3-N maximum at 30–40 m, immediately below the steep

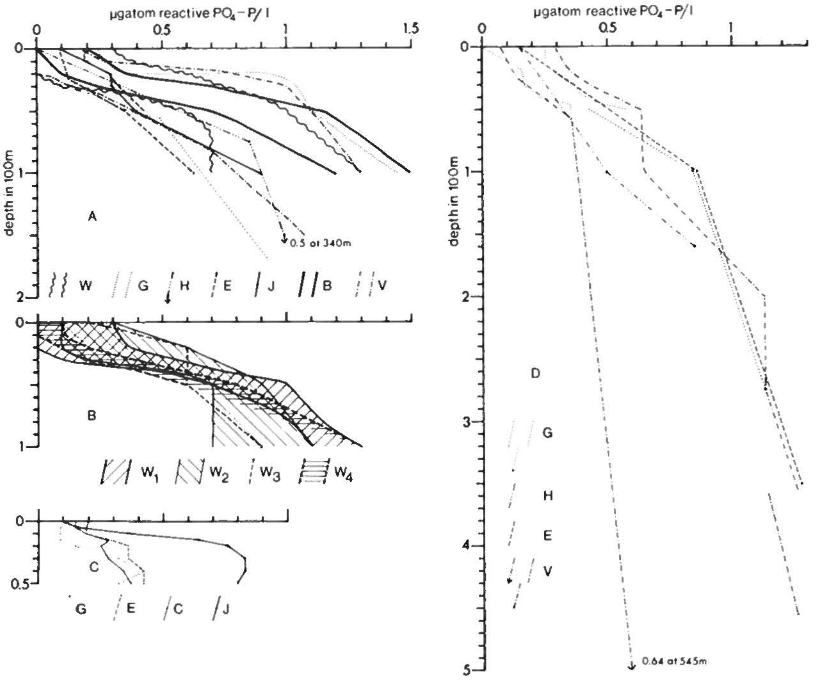


Fig. 57: Two curves show the extreme concentrations of PO_4-P in the hydrographic areas (Fig. 56) in July (A + B), Aug. (C), and Sept. (D). When less than 3 series are available, each one is included. In (B) W_1, W_2, and W_4 are hatched between curves.

month	July	July	July	July	July	July	July	July	July	July	July
area	W	G	H	E	J	B	V	W_1	W_2	W_3	W_4
no. of ser.	14	11	1	2	1	3	13	6	3	1	4
dates	14–31	2–29	6	6+26	29	23–29	26–31	14–31	22–26	27	15+31

month	Aug.	Aug.	Aug.	Aug.	Sept.	Sept.	Sept	Sept.
area	G	E	C	J	G	H	E	V
no. of ser.	1	1	1	1	7	1	1	4
dates	7	10	11	13	3–25	9	11	6+7

part of the surface halocline which resembles conditions existing at Atâ Sund (Fig. 58B).

O_2

The author did not measure O_2, but earlier data are available from both Disko Bugt and the Vaigat and numerous measurements have been made S of Disko Bugt (Jones & Folkard 1968). The saturation point of the water changes with temperature, and photosynthesis acts opposite to respiration by marine organisms and oxidation of dissolved organic matter in determining the degree of saturation at a particular depth which is also influenced by variations in stability and vertical mixing.

In the West Greenland Current over Store Hellefiskebanke S of Disko Bugt, high saturation values (110–130%) generally exist at the surface during the summer (2 in Fig. 59). Supersaturation extends to the bottom even as far down as to 75–300 m, and the values generally fall smoothly with depth to no less than 90%, even at 400 m. Following the spring bloom, however, production is poor, and the well mixed water over the shallow parts (50 m or less) of the bank – largely devoid of nutrients in June – exhibit saturation values of about 80%, or even less (× in Fig. 59) right to the bottom, where the highest values exist. Over the outer slopes, where nutrients are also at a minimum, supersaturation, however, still exists. Over the SW slopes, low saturation levels exist in the upper 40–75 m (at and above 1A in Fig. 59), and 85% is reached at greater depth, while over the NW and N slopes of the bank, S and W of area W, quite high (112–117%) surface values exist (above 2B in Fig. 59), but supersaturation goes no deeper than to 40–50 m, below which values of 75–90% exist at 100–200 m, beneath the cold winter minimum. Here, as in area W and in the Vaigat, a subsurface maximum of up to 128% is found – presumably in connection with a productive layer existing below the freshened surface layers at a depth of 15–25 m. As shown in Fig. 59, the shallowest (20–30 m) supersaturated surface layers are found in the Vaigat and W of Godhavn in the current leaving Disko Bugt. In the parts of Disko Bugt and the

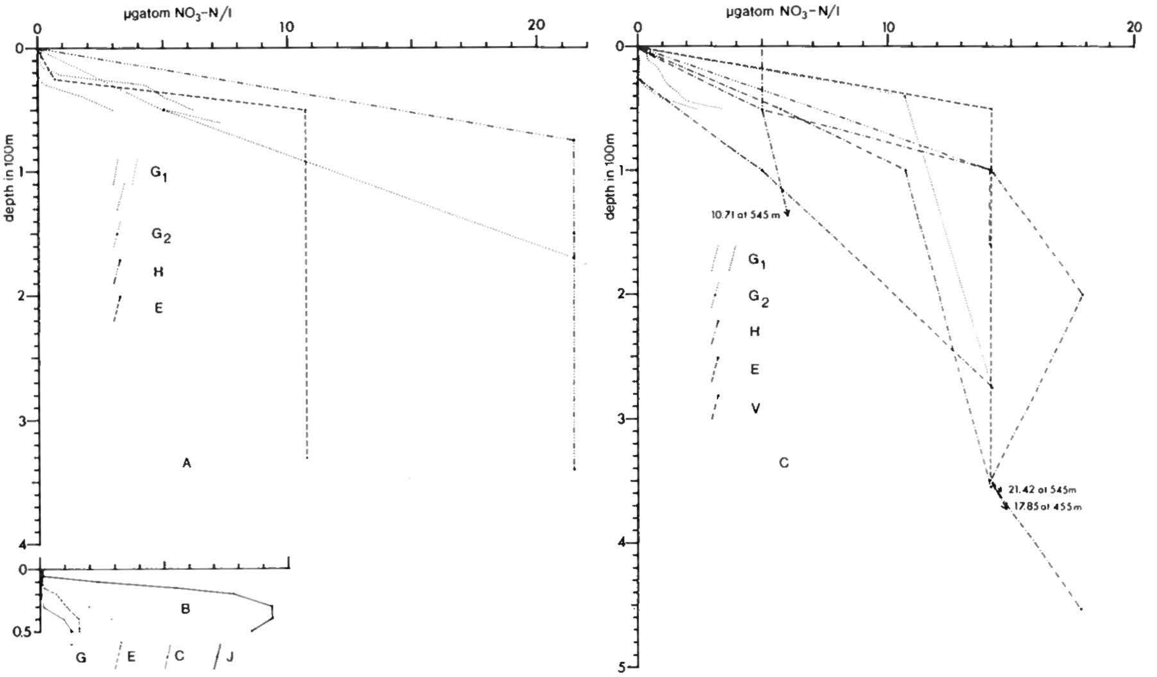


Fig. 58: Two curves show extreme concentrations of NO_3-N in the hydrographic areas (Fig. 58) in July (A), Aug. (B), and Sept. (C). When less than 3 series are available, each one is included. (B), and G_1 in (A) and (C) are from 1974 & 1975, and the remainder from 1928 (Hagen 1936).

month	July	July	July	July	Aug.	Aug.	Aug.	Aug.	Sept.	Sept.	Sept.	Sept.	Sept.
area	G_1	G_2	H	E	G	E	C	J	G_1	G_2	H	E	V
no. of ser.	5	1	1	1	1	1	1	1	3	1	1	1	4
dates	2–26	7	6	6	7	10	11	13	3–20	9	9	11	6+7

Vaigat, where freshened surface water stabilizes the upper layers, the oxygen profiles resemble conditions in Baffin Bay, where a shallow supersaturated surface layer generally is superimposed upon water of much lower oxygen content. At Egedesminde conditions of supersaturation resemble those generally found over the W slopes of Store Hellefiskebanke and the O_2% in the upper 200 m – excluding the freshened surface layers – drops, when going from Egedesminde to Godhavn and the areas W of Disko. The highest values below 200–300 m in Disko Bugt occur in the major channel between the islands in area H, where the deep warm part of the West Greenland Current primarily intrudes, while the lowest values are found in the eastern part of the Vaigat, inside the 245 m deep threshold separating it from Disko Bugt. Nowhere, however, are critically low values reached. Even lower O_2% values exist W of Disko and in Baffin Bay, especially below 200 m. The absolute oxygen values show characteristic profiles quite similar to the saturation values.

During the summer from June–July to Sept. (Fig. 59) the general heating of the upper 200 m raises the O_2% in most areas. The change is most apparent in the formerly cold layers off Godhavn, as in Baffin Bay and W of the area dealt with here. Unfortunately only one series from surface to bottom is available from Aug. This series demonstrates an apparent drop in the absolute values in the upper 50 m in spite of conditions of supersaturation existing in the upper 30 m. All series from Sept. exclude the upper 50 m, below which subsaturation exists everywhere. In absolute measure the only apparent rise in O_2 content is off Godhavn, in area H and W of the areas dealt with here, while to the S virtually no changes are recorded, except for a slight drop in the upper 200 m off Store Hellefiskebanke.

pH

The pH profiles shown in Fig. 60A and B follow the O_2 profiles for the same stations (Fig. 59) quite well. The decreasing pH values from the surface down through the combined thermo- and halocline is characteristic of the summer months off Godhavn, while in the well mixed water off Egedesminde pH values vary less. Measurements from off Atâ Sund north of Jakobshavn show that the pH values dropped abruptly down through the steep halocline, below which uniform values existed in the quite well mixed water rich in nutrients and dead algae found there (Fig. 61).

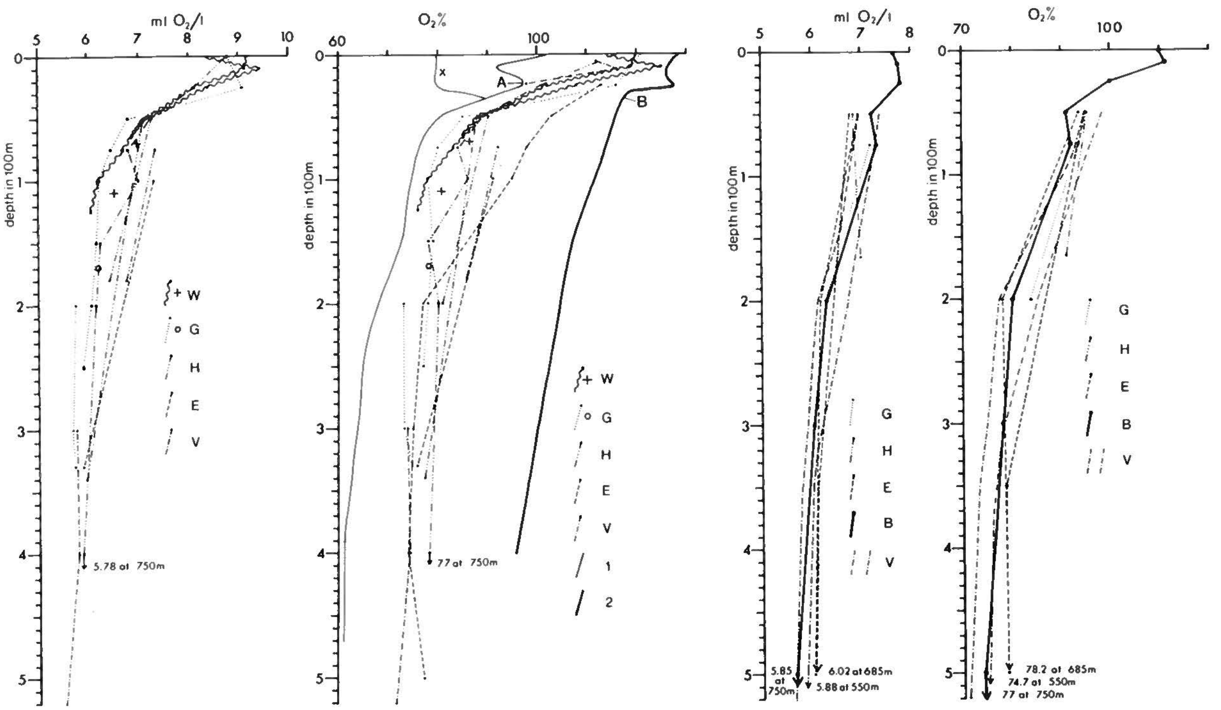


Fig. 59: Left: O_2 concentration (ml/l) in the hydrographic areas (Fig. 56) in June and July – all series shown. Centre left: Corresponding and some additional O_2 saturation (%) series plus curve 1 representing lowest, and curve 2 representing highest saturation values N of the 66th parallel outside the shallow areas of Store Hellefiskebanke, and × representing lowest values found in June over the shallow areas of Store Hellefiskebanke (NORWESTLANT 2). Values below A in curve 1 are from W of Disko and from Baffin Bay, and the remainder from the SW slopes of Store Hellefiskebanke. Values below B in 2 are from the greater part of the bank and the remainder from the N and NW slopes and from well off Disko Bugt. Centre right: O_2 concentration, and far right: Corresponding O_2 saturation in Aug. and Sept. In area V 2 curves indicate the extreme values.

	months	June	June	June	June	June	July	July	July	July	July	Aug.	Sept.	Sept.	Sept.	Sept.
	area	W	G	H	E	V	W	G	H	E	V	B	G	H	E	V
O_2/l	no. of ser.	2	1	1			2	2	3	1	1	1	1	1	2	8
	dates	28	29	29			13	7+29	6	6	29	15	9	9	9+11	6+7
$O_2\%$	no. of ser.	2	1	1	1	1	2	2	3	1	1	1	1	1	2	8
	dates	28	29	29	22	25	13	7+29	6	6	29	15	9	9	9+11	6+7

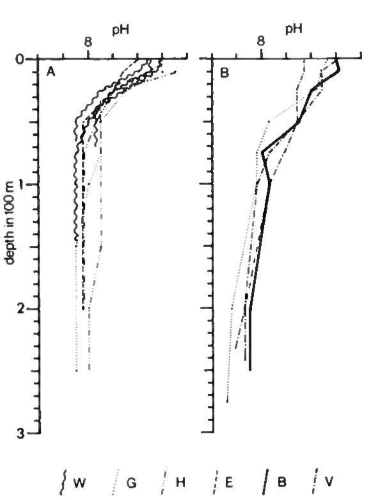


Fig. 60: A: pH in June and July, and B: pH in Aug. and Sept. Each series shown – parallel to O_2 concentration series in Fig. 59.

months	June	June	June	July	July	July	Aug.	Sept.	Sept.
area	W	G	H	W	H	E	B	G	V
no. of ser.	2	1	1	1	1	1	1	1	2
dates	28	29	29	13	6	6	15	9	6+7

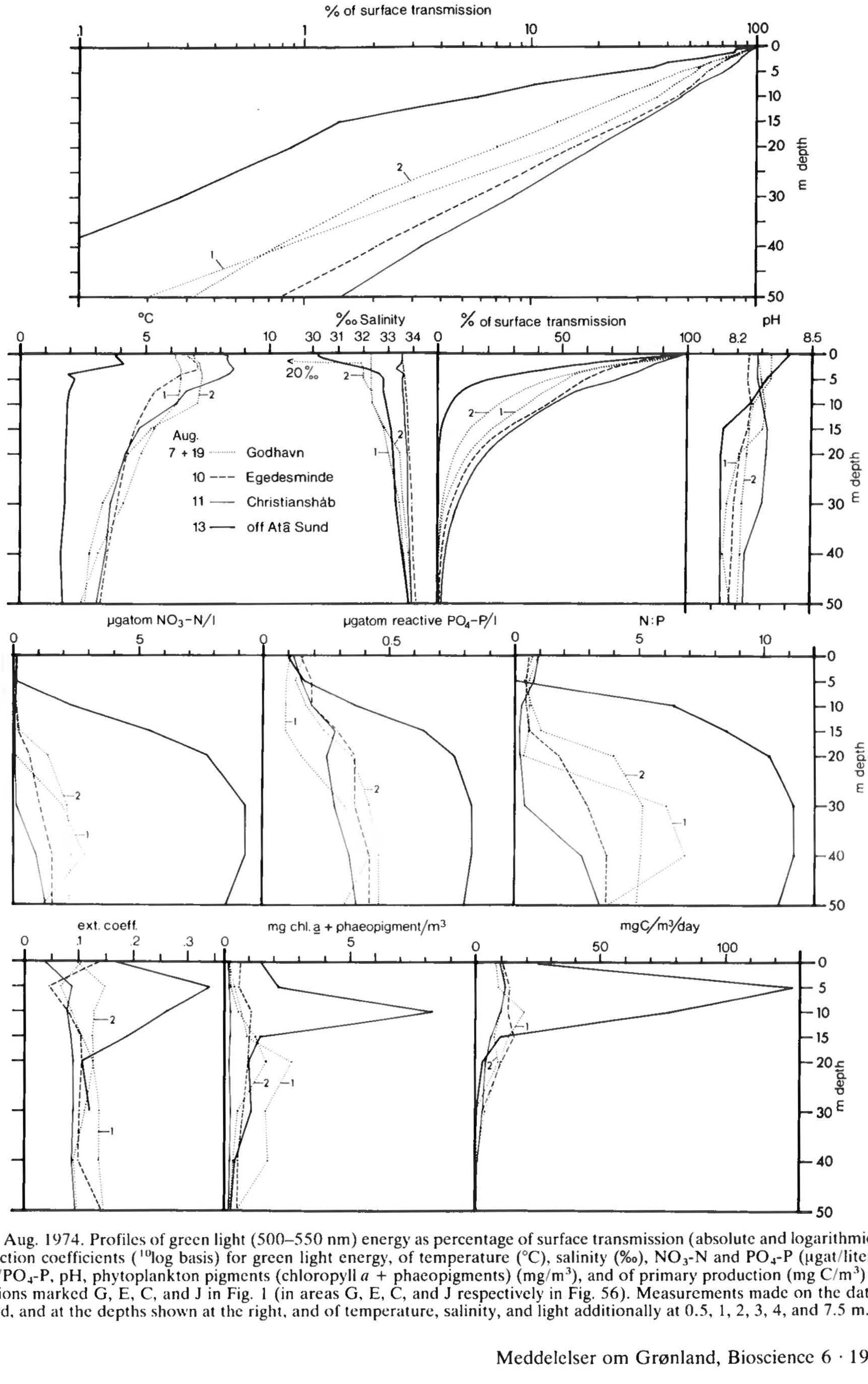


Fig. 61: Aug. 1974. Profiles of green light (500–550 nm) energy as percentage of surface transmission (absolute and logarithmic), of extinction coefficients (^{10}log basis) for green light energy, of temperature (°C), salinity (‰), NO$_3$-N and PO$_4$-P (µgat/liter), NO$_3$-N/PO$_4$-P, pH, phytoplankton pigments (chloropyll *a* + phaeopigments) (mg/m^3), and of primary production (mg C/m^3) at the stations marked G, E, C, and J in Fig. 1 (in areas G, E, C, and J respectively in Fig. 56). Measurements made on the dates indicated, and at the depths shown at the right, and of temperature, salinity, and light additionally at 0.5, 1, 2, 3, 4, and 7.5 m.

Other primary production measurements in Disko Bugt

Apart from the production measurements made at Godhavn and in Kangikerdlak only three other series have been made in Disko Bugt, one at Egedesminde on 10 Aug., one at Christianshåb on 11 Aug. and one off Atâ Sund N of Jakobshavn on 13 Aug. 1974 (Figs 1 & 61). Atâ Sund is very different from the other three stations shown in Fig. 61, with regard to hydrography and production. At depths below about 20 m the salinity profile is quite similar to the two shown from Godhavn, whereas above this depth a freshened surface layer about 5 m thick, originating from melting ice bergs and from effluents from Jakobshavn Isfjord, inhibits vertical mixing to a greater extent than at Godhavn. At Egedesminde and at Christianshåb the water is more saline and well mixed throughout the upper 50 m, whereas off Atâ Sund, the insulating effect of the freshened surface layer and the cooling effect of the huge ice bergs create very cold and isothermal conditions below a warmer surface layer of freshened water about 5 m thick. This is in sharp contrast to the higher temperature and sloping thermoclines characterising the temperature profiles below 3–10 m at the other three stations. At Godhavn, however, temperatures continue to drop with depth and reach 1.12°C at 90 m compared to 1.83°C at Atâ Sund at this depth.

Surface water of low salinity is clearly associated with turbidity which reaches an extreme at 5–10 m at Atâ Sund. Vertical mixing, sedimentation and a drop in chlorophyll content reduces turbidity towards Godhavn and the water is clearest at Christianshåb, where especially the upper 5 m have low extinctions compared to the other stations. The 1% depths are 18.6 m, 38.4 and 39.1 m, 48.4 m and 54.7 m respectively – the curves of Fig. 61 top taken from top to bottom.

Subsurface illumination is reflected in the depletion of nutrients and most clearly in that of NO_3-N, the concentration of which is lowest at Christianshåb, where turbidity is least, and greatest at Atâ Sund, where turbidity is most pronounced. Primary production again is greatest where nutrient concentrations begin to rise with depth, and by far the greatest just above the large nutrient reserve found below the euphotic zone at Atâ Sund, while it is lowest at Christianshåb. This high productivity at Atâ Sund is associated with a rise in pH in the upper 10 m, whereas pH in the nutrient rich deep water is very low. Chlorophyll *a* is found in greatest quantities just below the production maximum at Atâ Sund, as is generally the case at Godhavn, whereas chlorophylls are more evenly distributed at Egedesminde and at Christianshåb.

The high daily production rates per m^3 found at Atâ Sund are comparable to those of the spring and fall blooms at Godhavn, but since light extinction is very great, restricting production to a shallower surface layer than at Godhavn, production per m^2 is not as high. At Atâ Sund daily production on 13 Aug. 1974 was thus 1150 mg C/m^2 compared to 1925 mg C/m^2 on 14 May 1975, 1857 mg C/m^2 on 7 May 1975 and 1359 mg C/m^2 on 27 Aug. 1974 at Godhavn and to 339.7 mg C/m^2 and 211.4 mg C/m^2 at Egedesminde and Christianshåb respectively. Only four other series from Godhavn have daily production values of more than 500 mg C/m^2.

The immense production occurring at Atâ Sund is presumably in part a result of nutrient replenishment by the effluents from Jakobshavn Isfjord, and by melting ice bergs which are known to contain about 1.4 μgat NO_3-N/l (Parker et al. 1978 – measurements from the Antarctic ice cap). More important, however, is a continuous upwelling of cold water generated by the outflow of fresh surface water. This rising deep water has concentrations of NO_3-N and PO_4-P of as much as 21.4 μgat/l and 0.63 μgat/l respectively in Disko Bugt. As a result of this constant addition of nutrients to the euphotic zone the high production rates found at Atâ Sund probably are not part of a periodic bloom, but

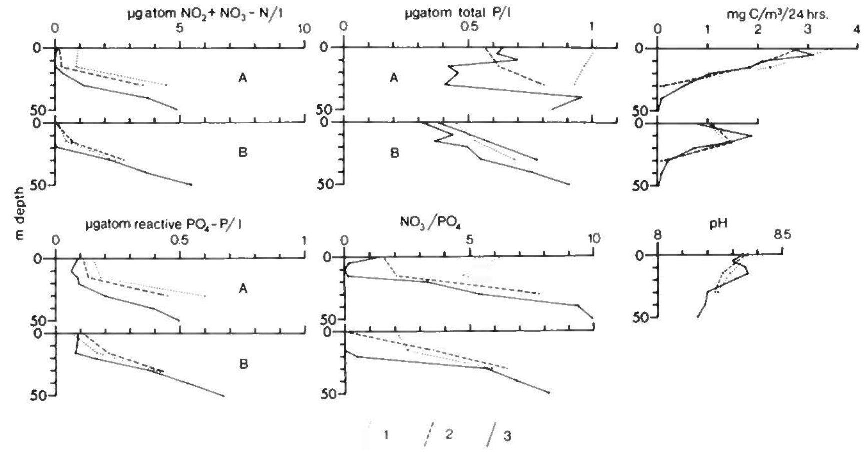


Fig. 62: 18 July (A) and 7 Aug. (B) 1973. Profiles of NO_3 + NO_2-N (μgat/liter), PO_4-P (μgat/liter), total P (μgat/liter), NO_3 + NO_2-N/PO_4-P, primary production (mg C/m³/24 hrs.), and pH, measured at 0, 15, and 30 m at the entrance to Godhavn harbour (1), and in Fortunebay (2), and at the 8 standard depths off Godhavn (3).

must occur continually throughout most of the spring, summer and fall, resulting in a yearly production which is very much higher than at Godhavn.

Primary production and nutrients inshore and offshore at Godhavn

There has been some speculation as to the effect from a small town such as Godhavn with ca. 1000 people upon the nutrient content and primary production of the marine environment in its immediate vicinity (Petersen 1964).

The depletion of nutrients in the upper 30 m, on two dates in 1973, when comparisons were made (Fig. 62), was greater offshore than inshore, where concentrations in July were highest in the entrance to Godhavn harbour. Here the total P content was highest also, but the concentration of reactive PO_4-P was not nearly as high as in Kangikerdlak, while, on the contrary, the NO_3-N content was much higher, yielding an exceptionally high NO_3-N: PO_4-P ratio compared to that found offshore, as well as in Kangikerdlak. This comparatively rich supply of NO_3-N found close to Godhavn in the harbour entrance, and at Fortunebay in the direction which the currents generally take close inshore from Godhavn, must derive from the town and its three processing plants for schrimp, fish, seal and whale.

Primary production measurements made at 0, 15 and 30 m, however, did not reflect this difference in nutrient content. Rather on the contrary, since production at 30 m, in fact, was least in the inshore waters, in spite of higher nutrient contents there. This is probably due to poorer illumination in the shallower more turbid inshore areas.

References

Andersen, O. G. Norden 1977a. Primary production, illumination and hydrography in Jørgen Brønlund Fjord, North Greenland. – Meddr Grønland 205 (4): 27 pp.

– 1977b. Primary production associated with sea ice at Godhavn, Disko, West Greenland. – Ophelia 16 (2): 205–220.

– 1981. The annual cycle of temperature, salinity, currents and water masses in Disko Bugt and adjacent waters, West Greenland. – Meddr Grønland, Biosci. 5: 33 pp.

Apollonio, S. 1973. Glaciers and nutrients in arctic seas. – Science 180: 491–493.

Berman, T. 1975. Size fractionation of natural aquatic populations associated with autotrophic and heterotrophic carbon uptake. – Mar. Biol. 33: 215–220.

B. H.= Bull. hydrogr. Cons. perm. int. Explor. Mer.

Boström, B. & Pettersson, K. 1977. The spring development of phytoplankton in Lake Erken. – Freshw. Biol. 7: 327–335.

Carlberg, S. R. (ed.) 1972. New Baltic manual with methods for sampling and analyses of physical, chemical and biological parameters. – I.C.E.S. Cooperative Res. Rep. Ser. A 29.

Cherry, R. D. & Higgo, J. J. W. 1978. Zooplankton fecal pellets and elements residence time in the ocean. – Nature 274: 246–248.

Cox, C. & Munk, W. 1956. Slopes of the sea surface deduced from photographs of sun glitter. – Bull. Scripps Instn Oceanogr. tech. Ser. 6: 401–488.

D. F. H. = Danish Fisheries and Marine Investigations, Charlottenlund Slot, DK-2920 Charlottenlund, Denmark.

Eppley, R. W., Rogers, J. N. & McCarthy, J. J. 1969. Half-saturation constants for uptake of nitrate and ammonium by marine phytoplankton. – Limnol. Oceanogr. 14: 912–920.

Friebele, C. S., Correll, D. L. & Faust, M. A. 1978. Relationship between phytoplankton cell size and the rate of orthophosphate uptake: in situ observations of an estuarine population. – Mar. Biol. 45: 39–52.

Glooschenko, W. A., Moore, J. E. & Vollenweider, R. A. 1972. The seasonal cycle of phaeopigments in Lake Ontario with particular emphasis on the role of zooplankton grazing. – Limnol. Oceanogr. 17: 597–605.

Hagen, S. K. 1931. Die Godthaabexpedition, 1928, Bericht über die chemischen Arbeiten. I. Meddr Grønland 72 (2): 28 pp.

– 1936. Die Godthaabexpedition, 1928, Bericht über die chemischen Arbeiten. 2. Meddr Grønland 78 (4): 36 pp.

Harvey, H. W. 1955. The chemistry and fertility of seawaters. – Cambridge University Press: 224 pp.

Jerlov, N. G. 1968. Optical oceanography. – Elsevier, New York: 194 pp.

Johnson, N. G. & Liljequist, G. 1938. On the angular distribution of submarine daylight and on the total submarine illumination. – Svenska hydrogr.-biol. Kommn Skr. Ny Ser. hydrogr. 14: 15 pp.

Jones, P. G. W. & Folkard, A. R. 1968. The distribution of phosphate, silicate and dissolved oxygen in the 0–100 m during Norwestlant 1–3. – Spec. Publs int. Commn NW. Atlant. Fish. 7(1): 57–63.

Lorenzen, C. J. 1967. Determination of chlorophyll and phaeopigments: spectrophotometric equations. – Limnol. Oceanogr. 12: 343–346.

Malone, T. C. 1971a. The relative importance of nannoplankton and net plankton as primary producers in tropical oceanic and neritic phytoplankton communities. – Limnol. Oceanogr. 16: 633–639.

– 1971b. The relative importance of nannoplankton and net plankton as primary producers in the California Current system. – Fish. Bull. U. S. 69: 799–820.

Martens, C. 1929. Hydrographical investigations during the "Michael Sars" Expedition, 1924. – Rap. P.-v. Réun. Cons. perm. int. Explor. Mer. 56(11): 29 pp.

McCarthy, J. J., Taylor, R. & Loftus, M. E. 1974. Significance of nannoplankton in the Chesapeake Bay Estuary and problems associated with the measurement of nannoplankton productivity. – Mar. Biol. 24: 7–16.

McLaren, I. A. 1969. Primary production and nutrients in Ogac Lake, a landlocked fiord on Baffin Island. – J. Fish. Res. Bd Canada 26: 1561–1576.

Nielsen, E. Steemann 1960. Dark fixation of CO_2 and measurements of organic productivity. With remarks on chemo-synthesis. – Physiologia Pl. 13: 348–357.

Parker, B. C., Heishell, L. E. & Thompson, W. J. 1978. Nonbiogenic fixed nitrogen in Antarctica and some ecological implications. – Nature 271: 651–652.

Parsons, T. R. & Takahashi, M. 1973. Environmental control of phytoplankton cell size. – Limnol. Oceanogr. 18: 511–515.

Petersen, G. Høpner 1964. The hydrography, primary production, bathymetry and "tagsaq" of Disko Bugt, West Greenland. – Meddr Grønland 159(10): 45 pp.

Platt, T. & Irwin, B. 1971. Phytoplankton production and nutrients in Bedford Basin, 1969–70. – Fish. Res. Bd Canada, Tech. Rep. 247: 172 pp.

Riis-Carstensen, E. 1936. The Godthaab Expedition, 1928. The hydrographic work and material. – Meddr Grønland 78(3): 101 pp.

Sauberer, F. 1962. Empfehlungen für die Durchführung von Strahlungsmessungen an und in Gewässern. – Mitt. Int. Verein. Limnol. 11: 77 pp.

Sauberer, F. & Dirmhirn, I. 1954. Über den Strahlungshaushalt der Ozeane auf der Nordhalbkugel. – Arch. Meteorol. Geophysik und Bioklimatol., Ser. B–A 6 (1/2): 113–127.

Sauberer, F. & Ruttner, F. 1941. Die Strahlungsverhältnisse der Binnengewässer. – Probleme Kosm. Phys. 11: 1–240.

Spence, C. & Steven, D. M. 1974. Seasonal variation of the chlorophyll *a*: phaeopigment ratio in the Gulf of St. Lawrence. – J. Fish. Res. Bd Canada 31(7): 1263–1268.

Strickland, J. D. H. 1958. Solar radiation penetrating the ocean. A review of requirements, data and methods of measurement, with particular reference to photosynthetic productivity. – J. Fish. Res. Bd Canada 15: 453–493.

Taguchi, S. & Platt, T. 1977. Assimilation of $^{14}CO_2$ in the dark compared to phytoplankton production in a small coastal inlet. – Est. Coast. Mar. Sci. 5: 679–684.

Vollenweider, R. A. 1955. Ein monogram zur Bestimmung des Transmissionskoeffizienten sowie einige Bemerkungen zur Methode seiner Berechnung in der Limnologie. – Schweiz. Z. Hydrol. 17(2): 205–216.

Yentsch, C. S. & Ryther, J. 1959. Relative significance of net plankton and nannoplankton in the waters of Vineyard Sound. – J. Cons. perm. int. Explor. Mer. 24: 231–238.

Meddelelser om Grønland, Bioscience

1979

1. Erik L. B. Smidt:
»Annual cycles of primary production and of zooplankton at Southwest Grenland«. 53 pp.

Annual hydrographic observations, measurements of primary production, and samplings of zooplankton were undertaken in Southwest Greenland waters in the 1950s and –60s. In the coastal area and at the entrance to Godthåbsfjord winter cooling normally extends to the bottom, resulting in a vertical mixing of the water and an effective replenishment of nutrients at the surface. The subsequent production rate is, therefore, high with an average annual gross production calculated to about 160 gC m^{-2}. In the inner fjord regions the stratification is normally much more stable with persisting warm bottom water, and the production is, therefore, lower here than in the coastal area. The seasonal variation in the relations between daylight, primary production, phosphate, and quantity of zooplankton is, presumably, representative of the coastal waters at SW Greenland. A maximum in primary production in spring is normally followed by another maximum in late summer. The number of animals in the microplankton samples from the upper 30 m (the productive layer) is at its maximum simultaneously with the second maximum of the primary production, while the maximum of the macroplankton biomass (taken by stramin net) extends until late autumn in the coastal and outer fjord regions.

A maximum of the macroplankton biomass during winter in the deep water layers in the inner Godthåbsfjord, caused by inflow of warm bottom water, stable stratification and cooled outflowing surface water acting as a barrier to the ascent of the animals, is assumed to be normal to the open, non-threshold, W Greenland fjords.

Seasonal vertical migration of the zooplankton is indicated by Hensen net hauls from different depths. There is a concentration of zooplankton in the upper water layers in April–September and a deeper concentration from autumn to spring.

Annual cycles of various animal groups are described for holoplankton and meroplankton, separately. Holoplankters are normally dominant, copepods being the most numerous group. Meroplankters, especially bottom invertebrate larvae, are relatively numerous in the microplankton in spring and summer with *Balanus* nauplii dominant in spring and lamellibranch larvae in the following months. In a special section on fish eggs and larvae it is shown *I.a.* that cod eggs and larvae are normally concentrated in the upper 50 m, where they are much exposed to temperature variations, while eggs and larvae of American plaice occur also in deeper water. This may partly explain why the cod stock is more vulnerable to low temperatures.

It is shown that the epipelagic plankton fauna in the survey area in terms of growth and mode of development is more similar to the arctic than to the boreal fauna. It could therefore be termed subarctic, which also corresponds to the environmental conditions in the area.

1980

2. Jean Just:
»Amphipoda (Crustacea) of the Thule area, Northwest Greenland: Faunistics and Taxonomy«. 61 pp.

The material reported on was collected in the Thule area, NW Greenland, in 1968 and includes 105 species. Four of these, *Aceroides goesi, Bathymedon antennarius, Monoculodes vibei* and *Parametopa crassicornis,* are new to science. An additional 6 species are new to Greenland, while 9 species have previously been found in E Greenland but not in W Greenland. Four genera, *Lembos, Arrhinopsis, Arctopleustes* and *Parametopa,* are recorded from Greenland for the first time.

Specimens belonging to 15 additional taxa are for various reasons not referred to species. Major taxonomic problems, warranting broadly based revisions, are outlined in the genera *Byblis, Gitanopsis, Ischyrocerus, Tmetonyx, Monoculodes* and *Stenula.* Three different forms of *Paroediceros lynceus* are discussed.

All known amphipod species from the Thule area are included in an annotated list. Forty-nine taxa are discussed and figured.

1980

3. H. Meltofte, M. Elander and C. Hjort:
»Ornithological observations in Northeast Greenland between 74°30′ and 76°00′ N. lat. 1976« 53 pp.

The results of one summer's work in central Northeast Greenland are presented. The avifauna in the country traversed on several extensive survey trips is described. More intensive studies were made in an 18.2 km² census area on southernmost Hochstetter Forland. Here the populations were followed throughout the breeding season, and information on arrival, pre-laying period, population densities, habitat and nest site selection, breeding schedule, clutch size, hatching success, re-nesting, non-breeders, moult, post-breeding activities and departure is given. Special attention is given to *Clangula hyemalis, Somateria spectabilis, Anser brachyrhynchus, Arenaria interpres, Calidris maritima, Calidris alpina, Calidris alba, Phalaropus fulicarius* and *Stercorarius longicaudus.* An extremely high predation pressure was caused by *Alopex lagopus,* and this is discussed in relation to lemming abundance and environmental conditions.

1981

4. Peter Milan Petersen: "Variation of the population structure of Polygonum viviparum L. in relation to certain environmental conditions." 19 pp.

Populations of *Polygonum viviparum* L. have been studied at Godhavn in Greenland (69° 14′ N, 53° 31′ W), at 30 sites within an investigation area of approx. six km². At each site, the age structure of the population was described after the individuals had been classified on the basis of the morphology of the rhizome. Other population parameters investigated are the total number of individuals (1 – 2,860 per m²), number of recently established individuals (0 – 1,720 per m²), number of flowering individuals (0 – 850 per m²), number of bulbils produced (0 – 17,870 per m²), and dry weight of standing crop (0.6 – 281 g per m²); the numbers in the brackets give the total range for the 30 sites. The flowering individuals have been characterized by the age class in which flowering first occurs, the mean dry weight of the vegetative parts (0.06 – 0.94 g) and the mean number of bulbils (9± 4 – 114 ± 46). – The environmental parameters studied include height above sea level, slope and direction of slope, soil water content, loss on ignition, bulk density, pH, exchangeable K, 0.2 N H_2SO_4-soluble P, C/N, soil temperature, time of disappearance of the snow, soil movement, and degree of cover of the vegetation. The sites have been assigned to six groups which are defined with emphasis on those factors which are assumed to be limiting: 1. Sites with soil movement, 2. Sites where the snow is late in disappearing, 3. Sites with waterlogged soil, 4. Well-drained sites on level or slightly sloping ground, 5. Steep slopes, exposed to the sun, and 6. Sites where competition for light is an important factor. Within each of the groups, the sites show a number of common features, especially as regards relative values referring to the population structure, and various features characterizing the plants. It is suggested that the large variation in the population parameters mentioned above occurs mainly because individuals of *Polygonum viviparum* of a different age are in a different way and to a different degree influenced by the environmental conditions. At the same time, the bulbil gain from and loss to the surroundings is stressed as important for the size of a population.

Peter Milan Petersen, Institute of Plant Ecology, University of Copenhagen, Ø. Farimagsgade 2 D, DK-1353 Copenhagen K.

Meddelelser om Grønland, Geoscience

1979

2. Sven Karup-Møller and Hans Pauly: »Galena and associated ore minerals from the cryolite at Ivigtut, South Greenland«. 25 pp.

Silver- and bismuth-rich galena concentrates have been produced for more than 70 years as a byproduct in the dressing of the crude cryolite from Ivigtut, South Greenland.

Concentrates from the years 1937 to 1962 contained from 0.44 % Ag and 0.74 % Bi to 0.94 % Ag and 1.93 % Bi. Conspicuous increases in the content of these elements appeared twice within this time interval, namely in 1955 and in 1960. Thus it seems that crude cryolite from specific areas within the mine carried galena high in silver and bismuth. This promoted a detailed study of the common Ivigtut galena and associated sulphides.

An outline of the geological setting of the deposit is given. The deposit is divided into two main bodies – the cryolite body and the quartz body. Both are subdivided into units characterized by their content of siderite and fluorite. Galena samples from these units and from rock types surrounding the deposit have been studied.

Galena from units characterized by siderite follows the compositional pattern found in the galena concentrates, whereas the sparse galena mineralizatiions from units characterized by fluorite contain much smaller amounts of silver and bismuth, less than 0.2 %. However, within the fluorite-bearing units, two peculiar parageneses reveal high contents of silver and bismuth expressed by the presence of particular minerals such as marildite-aikinite and gustavite cosalite respectively.

Further trace element studies on selected galena samples emphasize Sn and Te as chemically characteristic of the galena and of the sulphide-carbonate phase of the deposit.

The temperature of formation of the main part of the deposit is placed at 550–400°C, and between 300 and 200°C certain parts of the fluorite cryolite and the fluorite zone.

1980

3. John C. Rucklidge, Charles Kent Brooks and Troels F. D. Nielsen: »Petrology of the coastal dykes at Tugtilik, southern East Greenland«. 17 pp.

Dolerite and lamprophyre dikes from Tugtilik in the southern part of the onshore exposure of the East Greenland coastal dike swarm are described. The dolerites, which are earlier, are similar to other tholeiites from the dike swarm and the plateau basalts and also to many Icelandic tholeiites. Transitional varieties have been identified from the Angmagssalik district. The lamprophyres have a nephelinitic composition and are rich in phenocrysts and xenocrysts. In one case, abundant low pressure inclusions occur. Rocks identical to these lamprophyres have not previously been described from Greenland but are well known, for instance, in the African Rift.

1981

B. H. Scott: "Kimberlite and lamproite dykes from Holsteinsborg, West Greenland". 24 pp.

Numerous kimberlite and lamproite dykes occur to the south and east of Holsteinsborg in Central West Greenland. This paper gives details of the petrography, mineral chemistry, age relations and geochemistry of the dykes.

The kimberlites are composed of macrocysts of olivine, phlogopite, rare ilmenite and garnet in a matrix of olivine, phlogopite, diopside, perovskite, spinel, serpentine, carbonate and apatite. They can mostly be classified as clinopyroxene-phlogopite hypabyssal kimberlites. Mantle-derived inclusions are found in some of the dykes and include lherzolites, wehrlites, harzburgites and, most commonly, dunites. Both coarse and porphyroclastic inclusions occur. Garnet-granulites and eclogites, although rare, are present.

The lamproites have variable mineral assemblages and textures but the main constituents are phenocrysts of pseudoleucite, olivine, phlogopite and clinopyroxene set in a groundmass of phlogopite, potassic richterite, diopside, pseudoleucite and potassium feldspar. The mineralogy of these dykes is a reflection of unusual ultrapotassic, magnesian whole-rock compositions.

Instructions to authors

Manuscripts will be forwarded to referees for evaluation. Authors will be notified as quickly as possible about acceptance, rejection, or desired alterations. The final decision rests with the editor. Authors receive two page proofs. Prompt return to the editor is requested.

Alterations against the ms. will be charged to the author(s). Twenty five offprints are supplied free. Order form, quoting price, for additional copies accompanies 2nd proof. Manuscripts (including illustrations) are not returned to the author(s) after printing unless especially requested.

Manuscript

General. – Manuscripts corresponding to less than 16 printed pages (of 6100 type units), incl. illustrations, are not accepted. Two copies of the ms. (original and one good quality copy), each complete with illustrations should be sent to the Secretary.

All Greenland place names in text and illustrations must be those authorized. Therefore sketch-maps with all the required names should be forwarded to the Secretary for checking before the ms. is submitted.

Language. – Manuscripts should be in English (preferred language), French, or German. When appropriate, the language of the ms. must be revised before submission.

Title. – Titles should be kept as short as possible and with emphasis on words useful for indexing and information retrieval.

Abstract. – An English abstract should accompany the ms. It should be short, outline main features, and stress novel information and conclusions.

Typescript. – Page 1 should contain: (1) title, (2) name(s) of author(s), (3) abstract, and (4) author's full postal address(es). Large mss. should be accompanied by a Table of contents, typed on separate sheet(s). The text should start on p. 2. Consult a recent issue of the series for general lay-out.

Double space throughout and leave a 4 cm left margin. Footnotes should be avoided. Desired position of illustrations and tables should be indicated with pencil in left margin.

Underlining should only be used in generic and species names. The use of italics in other connections is indicated by wavy line in pencil under appropriate words. The editor undertakes all other type selection.

Use three or fewer grades of headings, but do not underline. Avoid long headings.

References. – Reference to figures and tables in the text should have this form: Fig. 1; Figs 2–4, Table 3. Bibliographic references in the text are given as: Shergold (1975: 16) and (Jago & Daily 1974b).

In the list of references the following usage is adopted:

Journal: Macpherson, A. H. 1965. The origin of diversity in mammals of the Canadian arctic tundra. – System. Zool. 14: 153–173.

Book: Marsden, W. 1964. The lemming year. – Chatto & Windus, London: xxx pp.

Chapter (part): Wolfe, J. A. & Hopkins, D. M. 1967. Climatic changes recorded by Tertiary landfloras in northwestern North America. – In: Hatai, K. (ed.), Tertiary correlations and climatic changes in the Pacific. – 11th Pacific Sci. Congr. Tokyo 1966, Symp.: 67–76.

Title of journals should be abbreviated according to the last (4th) edition of the World List of Scientific Periodicals (1960) and supplementary lists issued by BUCOP (British Union-Catalogue of Periodicals). If in doubt, give the title in full.

Meddelelser om Grønland, Bioscience should be registered under *Meddelelser om Grønland.* Example (with authorized abbreviations): *Meddr Grønland, Biosci.* 1, 1979.

Illustrations

General. – Submit two copies of each graph, map, photograph, etc., all marked with number and author's name. Normally all illustrations will be placed within the text; this also applies to composite figures.

All figures (incl. line drawings) must be submitted as glossy photographic prints suitable for direct reproduction, i.e. having the format of the final figure. Do not submit original artwork. Where appropriate the scale should be indicated in the caption or in the illustration.

The size of the smallest letters in illustrations should not be less than 1.3 mm. Intricate tables are sometimes more easily reproduced from line drawings than by type-setting.

Colour plates may be included at the author's expense, but the editor should be consulted before such illustrations are submitted.

Size. – The width of figures must be that of a column (76.5 mm), 1½ column (117 mm) or of a page (157 mm). Remember to allow space for captions below full page figures. Maximum height of figures (incl. captions) is 217 mm. Horizontal figures are preferred.

If at all possible, fold-out figures and tables should be avoided.

Caption. – Captions (two copies) to figures should be typed on separate sheets.

Meddelelser om Grønland

Bioscience
Geoscience
Man & Society

Published by
The Commission
for Scientific
Research
in Greenland

AiO Tryk as, Odense