

Late winter chlorophyll *a* distributions in the Weddell Sea

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ABSTRACT: As part of the Weddell Polynya Expedition to the Weddell Sea (in the vicinity of 2° E/60° S) during October, and November, 1981, we report measurements of chlorophyll *a* and phytoplankton photosynthesis. Chlorophyll *a* measurements were made in 3 different environments: beneath the pack ice, in pack ice cores, and in the water column in the ice edge zone (IEZ, defined as 6/10's-1/10 ice cover). Photosynthesis measurements were made on samples from beneath the pack ice and from a station at the IEZ. Chlorophyll *a* values in the mixed layer beneath the pack ice average 12 mg m⁻². Within the IEZ (at 6/10's coverage) water column chlorophyll *a* doubles. Compared to values beneath the pack ice, the IEZ is characterized by a localized ten-fold increase in surface chlorophyll *a* (1 to 2 mg m⁻²). Photosynthesis parameters likewise increase at the ice edge, and a rate of primary production of 300 to 400 mg m⁻² d⁻¹ is estimated for this region. Significant amounts of chlorophyll *a* are found near the base of the pack ice column, and evidence is presented which suggests an active biological community living within the pack ice. Overall, the data are consistent with the idea that phytoplankton distributions are regulated by the availability of light. Furthermore, the data indicate the importance of the IEZ to primary production in the Southern Ocean.

INTRODUCTION

The seasonal dynamics of the production ecology of the surface waters surrounding Antarctica are distinguished by uniformly low temperatures south of the Antarctic Convergence (e.g. Gordon and Molinelli, 1982), extremes of solar irradiance, and substantial variability in sea ice. However, ideas concerning controlling factors of production have come largely from observations made in the austral summer. There are few data sets from winter (Hart, 1942; Burkholder and Burkholder, 1967), or from months of maximum ice extent, and discussion continues as to the relative importance of such factors as temperature, nutrients and irradiance to the dynamics of productivity in the Southern Ocean (e.g. Holm-Hansen et al., 1977; El-Sayed, 1978). The search for major environmental influence is important for deriving estimates of production as well as for being able to predict seasonal and areal variability. Also, because logistical support is difficult and expensive in the Southern Ocean, there are potential benefits in being able to predict rates of production from more easily measured, and perhaps remotely sensed, environmental factors.

Unlike most of the world's oceans, nutrients are

abundant in Antarctic Surface Water (AASW) (Gordon and Molinelli, 1982). Nutrient levels seldom drop below 1 µg-at PO₄-P l⁻¹, 10 µg-at NO₃-N l⁻¹ and 20 µg-at Si (OH)₄-Si l⁻¹ anywhere south of the Antarctic convergence. While significant nutrient variability exists, nutrient levels are well above thresholds where growth of phytoplankton might be considered nutrient-limited (e.g. Eppley et al., 1969; Walsh, 1971). Biggs (1978) reports low ammonium concentrations in the AASW, in spite of high concentrations of other nutrients, and possibly high turnover rates for this substrate. Whether these low concentrations affect rates of production is not clear. Ammonium is nearly always the preferred nitrogen source for phytoplankton in a wide variety of environments and under a wide range of physico-chemical conditions (e.g. McCarthy et al., 1977). The same is true of the Antarctic, at least in austral summer (Glibert et al., 1982), even though concentrations of ammonium are 1 to 2 orders of magnitude lower than nitrate. Olson's (1980) winter data from the Scotia Sea shows equal preference for nitrate and ammonia. It seems, therefore, that what has to be explained is the non-depletion of nitrate. It is possible that light or temperature limitation makes ammonium uptake more favorable energetically (Bates, 1976;

Slawyk, 1979; Syrett, 1981) to the extent that nitrate cannot be fully utilized.

Low temperatures are the probable cause of the uniformly low assimilation numbers characteristic for Antarctic waters (Eppley, 1972). Neori and Holm-Hansen (1982) have clearly shown a temperature effect, suggesting that Antarctic phytoplankton are at least facultative psychrophiles. Bunt (1968) has also reported experimental evidence showing a temperature influence on photosynthesis in Southern Ocean phytoplankton. While temperature probably limits physiological rates, Walsh (1971) has found temperature to be of minor importance in explaining variations in phytoplankton standing stock on transects with water temperature ranging from 6 to -1°C .

Light intensity, by virtue of its strong annual and areal variability, seems more likely than either nutrients or temperature to regulate primary production and the relative distribution of standing stocks in the Antarctic on a seasonal basis. The data of Hart (1942) show large increases in standing stock in summer relative to data collected in winter. The large variability in ice cover must also be considered. Ice cover ranges from a maximum in September and October of 20 million km^2 to 3 million km^2 in February (MacKintosh, 1972). The presence of ice inhibits air/sea exchanges and wind-induced mixing, and also markedly diminishes solar irradiance available for photosynthesis to the water column below. The formation of ice destabilizes the surface layer via the input of brine and consequent convective mixing. Conversely, the seasonal deterioration of the ice pack may stabilize, as well as provide seed populations for, the water column. For within-season studies, however, light intensity regulation is more difficult to demonstrate (Walsh, 1971), and there can be large spatial variations in primary production during the summer months (El-Sayed, 1970; El-Sayed and Weber, 1982). Large spatial variations could be due to hydrographic features or phenomena which increase the availability of light to phytoplankton, but oftentimes in the past, station-spacing on Antarctic expeditions was simply not adequate to isolate these.

During October and November, 1981, a joint US-USSR oceanographic program, The Weddell Polynya Expedition, was undertaken, one of the primary objectives of which was to obtain a comprehensive data set on winter or early spring conditions in the Southern Ocean. The Expedition was carried out aboard the Soviet ship 'Mikhail Somov' (length: 133 m, beam: 18.8 m) of the Arctic and Antarctic Research Institute of Leningrad. We made measurements of photosynthesis and chlorophyll *a* on water column samples and measured distributions of chlorophyll *a* in pack ice from mid-October to mid-November, 1981, that is during

months of near-maximum ice extent. We present evidence consistent with the idea that the distribution and production of phytoplankton is regulated by the availability of light.

METHODS

The horizontal variability of chlorophyll *a* was measured by *in vivo* fluorescence in water continuously pumped from 4 m depth through a Turner Designs Model 10 fluorometer. Conductivity and temperature were measured simultaneously. Details of the system, its operation, calibration and the data reduction can be found in Marra et al. (1982a). This system was operated continuously after R.V. 'Mikhail Somov' entered the pack ice, however, fluorescence values are uniformly low and data featureless. We found no evidence that algae from sea ice were contaminating the signal. The vertical distribution of chlorophyll *a* was determined on samples from Niskin bottles in the upper 100 to 150 m of the water column. Chlorophyll *a* was also determined at various depths in pack ice cores, obtained with a CRREL ice-auger and sectioned while still frozen aboard ship (Clarke and Ackley, 1984). Standard chlorophyll *a* analyses were immediately performed on melts of the section (Holm-Hansen et al., 1965).

During one foray onto the pack ice to collect ice cores, measurements of light attenuation through the ice were made using a Lambda Instruments underwater quantum sensor. For measurements on the ship, this sensor agreed well with a radiometer mounted on the mast of R.V. 'Mikhail Somov' assuming that photosynthetically active irradiance (as measured by the quantum sensor) is 43 % of the total (downward) irradiance measured by the radiometer (Withrow and Withrow, 1956). Irradiance values from the R.V. 'Mikhail Somov' radiometer were recorded daily and are here reported in units of ly d^{-1} .

Rates of photosynthesis were determined by incubating duplicate near-surface (3 to 10 m depth) seawater samples in the presence of $\text{NaH}^{14}\text{CO}_3$ (5 μCi). All samples were taken between 0900 and 1100 h to minimize variability which might be caused by diel changes in photosynthesis parameters. Samples were collected at Stations 19, 21, 22, 34 and 36, and also at several locales between stations to ensure the proper time of collection. The samples were incubated under a range of light intensities in a fluorescent light incubator for 3 to 6 h. Temperatures in the incubator were kept at 1 to 2°C above *in situ* by means of a refrigerated circulating bath. According to the data of Neori and Holm-Hansen (1982), this small temperature difference should not result in bias. The incubations were terminated by filtering the samples onto Millipore HA mem-

brane filters, which were then placed in glass scintillation vials with 10 ml of a toluene-based, water-compatible fluor (Bakerfluor). Upon return to the laboratory, the samples were counted on a Beckman LS100 liquid scintillation counter equipped with automatic external standardization. Photosynthesis vs. irradiance (P^b vs. I) data were fitted to the equation

$$P^b = P^{b\max} \cdot \tanh(\alpha I / P^{b\max}) - R \quad (1)$$

of Jassby and Platt (1976) by the non-linear regression techniques described in Malone and Neale (1981). Here, $P^{b\max}$ = light saturated rate of photosynthesis normalized to chlorophyll *a* concentration; α = initial slope of the curve; R = computed photosynthetic (respiration) rate at zero irradiance. Average errors in α and $P^{b\max}$ were typically 10 and 30 % of the reported values, respectively.

RESULTS

Fig. 1 shows the cruise track of R.V. 'Mikhail Somov' and station positions (CTD/rosette casts, ice cores, and expendable bathythermograph observations) during the cruise. The ship entered the ice on 20 October, 1981, and departed on 14 November, 25 d later. The positions of the nominal ice edges (3/10's coverage) are shown at these times in Fig. 1. The fact that the ice

edge defined this way is further south on 14 November than on 20 October as much represents variability in the position of the ice edge as it does a net reduction in the pack ice cover over the period of the cruise. The nominal ice edge itself occurs in a mixed zone of open water and variably sized floes (Ackley and Smith, 1983), indicative of a dynamic region of general ice decay and even some new ice formation. We have defined the ice edge zone (Fig. 2) as lying between 1/10–6/10's ice cover.

Fig. 2, from Gordon and Huber (1982), illustrates the oceanographic setting for the biological measurements. It also shows surface parameter traces collected while the ship was underway and transiting the ice edge zone (IEZ). The stations in the IEZ show meso-scale features of Circumpolar Deep Water (CDW; e.g. Station 36) which are not apparent either to the north or south. Surface water temperatures in and south of the IEZ never vary more than a few hundredths of a degree above -1.8°C , the surface freezing temperature. North of the ice edge zone, surface water temperatures gradually warm. Mixed layer depths vary from about 60 to 120 m. There is approximately a 2-fold increase in chlorophyll *a* fluorescence localized to the IEZ. Concurrent with this are negative anomalies in surface salinity and in nutrient concentrations. The surface chlorophyll *a* distributions derived from these

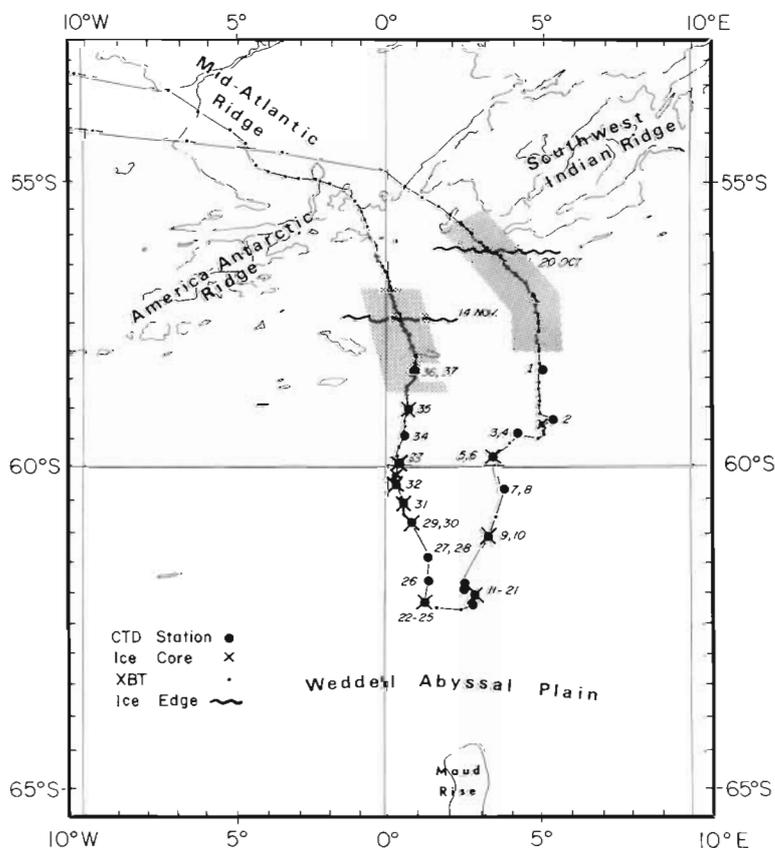


Fig. 1. Bathymetric map showing cruise track and station positions during the Weddell Polynya Expedition. The line defining the ice edge corresponds to about 3/10's ice coverage, and the shaded area defines the ice edge zone (IEZ). R.V. 'Mikhail Somov' entered the ice on 20 Oct, 1981, and departed 25 d later on 14 Nov

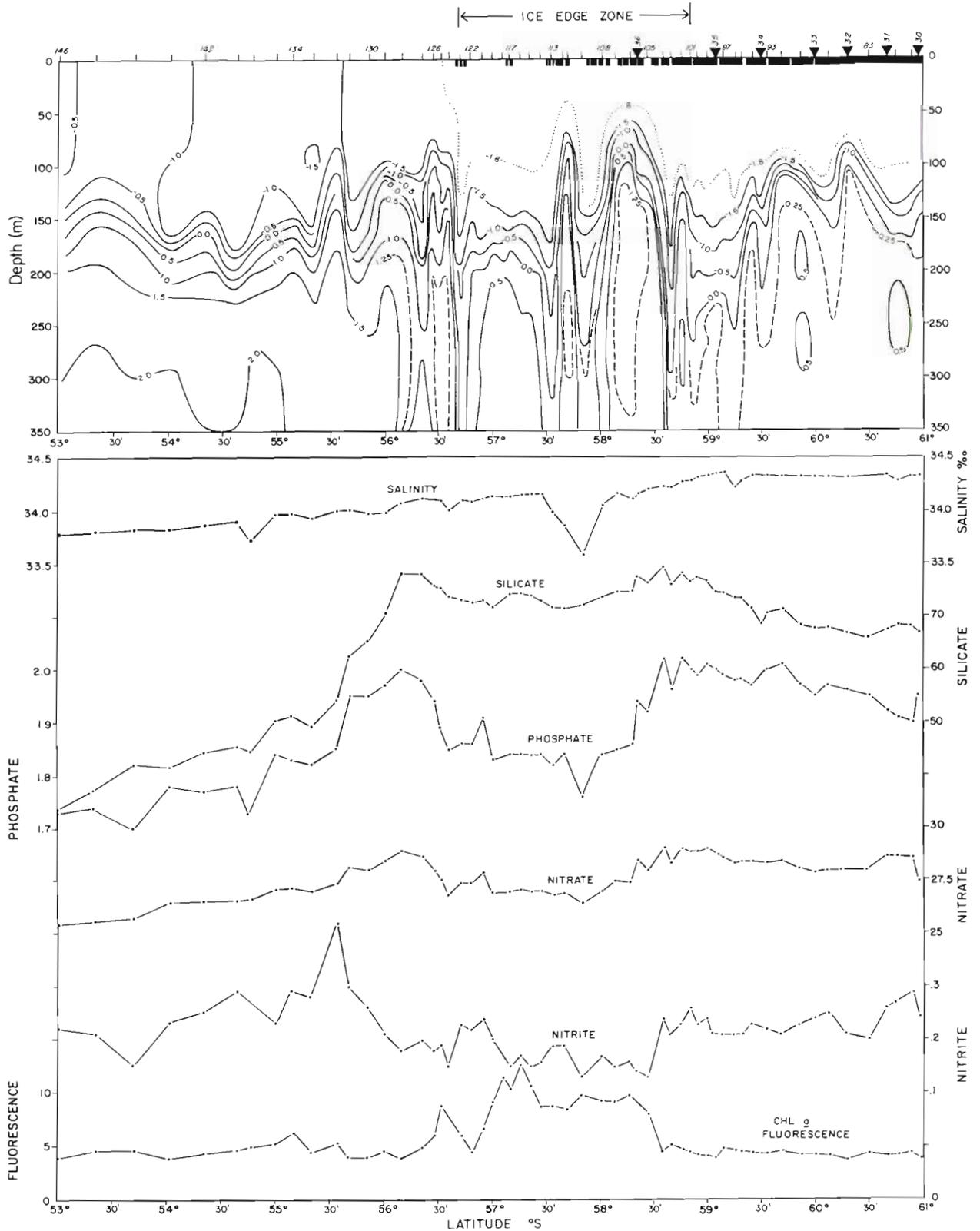


Fig. 2. Adapted from Gordon and Huber (1982). Depth vs. distance transect through the IEZ, approximately along the Greenwich Meridian. CTD stations (30 to 36) and positions of expendable bathythermograph launches (80 to 146) are indicated across the top, as is relative ice cover (thick solid line). Contours of temperature are given in °C. Salinity values were determined on an Autosal; nutrient values are courtesy of J. Jennings and were determined by Autoanalyser. Chlorophyll *a* fluorescence is in relative units. These values were sampled from the continuous fluorescence and temperature record

fluorescence values are discussed in more detail below.

Fig. 3 compares water column distributions of chlorophyll *a* for a station in the pack ice field and Station 36 in the IEZ (Fig. 1 and 2). Table 1 compares various environmental and biological variables for the pack ice and Station 36. The distribution of chlorophyll *a* in the water column beneath the pack ice (Station 15) shown in Fig. 3 is typical for all stations occupied in

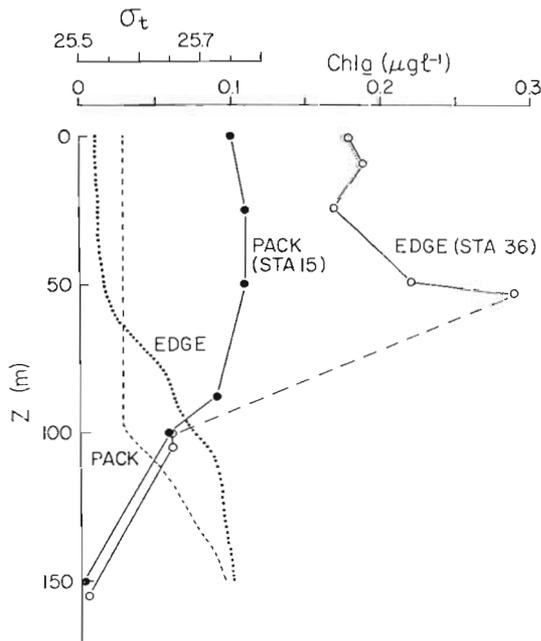


Fig. 3. Comparison of depth profiles of chlorophyll *a* and sigma- t (σ_t) between a station in the pack ice (STA 15) and in the IEZ (STA 36)

that area. Concentrations are low and uniform down to the pycnocline, and then decrease to near zero. The decrease in chlorophyll always occurred at the same depth as the pycnocline. Integrated chlorophyll *a* above the pycnocline ($n = 17$) averages 11.7 ($SD = \pm 2.67$) mg m^{-2} . At Station 36, in the IEZ, water column chlorophyll *a* doubles to 21.9 mg m^{-2} . This increase is associated with a much shallower isopycnal layer and of course, less ice cover. Thus the increase in phytoplankton biomass, as indicated by chlorophyll *a*, may be due to an increase in the availability of light for growth through an increase in stratification and a reduction in ice cover.

This feature in the data is borne out by some biological characteristics of the populations as well (Table 1). The P^b vs. I curve parameters (Equation 1, P^b max and α), increase dramatically in the sample from Station 36; the approximately 2.5x difference in P^b max for the ice edge station is significant at $P < 0.05$ (Fig. 4). The populations beneath the pack ice, although the

Table 1. Comparison of environmental and biological variables between stations occupied in the pack ice (mean \pm S.D.) and the station at the ice edge zone, Station 36 ($58^\circ 21.9' \text{S} / 00^\circ 49.2' \text{W}$). Number of observations (n) in parentheses where means of observations are reported

Variables	Pack ice	Station 36
Sea surface temperature ($^\circ\text{C}$)	-1.81	-1.78
Surface irradiance (1y d^{-1})	115 ± 19 ($n=8$)	94
Nitrate-nitrogen ($\mu\text{g-at l}^{-1}$)	28.4	29.1
Ice cover (tenths)	9-10	6
Euphotic zone depth ($1\% I_0$) (m)	2	~ 70
Chlorophyll <i>a</i> (mg m^{-2})	11.7 ± 2.6 ($n=17$)	22.0
α [$\text{mgC (mg Chl } a)^{-1} \text{ h}^{-1}$ ($\mu\text{Einst m}^{-2} \text{ s}^{-1})^{-1}$]	0.012 ± 0.009 ($n=8$)	0.027
P^b_{max} [$\text{mgC (mg Chl } a)^{-1} \text{ h}^{-1}$]	1.34 ± 0.254	3.82

euphotic zone is only a few m deep, exhibit no significant photoinhibition. However, there is a 20% decrease in photosynthesis at the highest irradiance in the IEZ sample. We have no explanation for this difference in photoinhibitory behavior.

The continuous measurement of chlorophyll *a* fluorescence on the transect exiting the pack ice field (Fig. 2) allows a further evaluation of the increase in biological activity at the ice edge. Station 36 (Fig. 3) occurs at the southern edge of a localized increase in surface chlorophyll *a* within the IEZ. Surface chlorophyll *a* increased about fourfold while the ship drifted to the east on Station 36. Upon getting underway, chlorophyll *a* continued to rise, within 10 km reaching 1 mg m^{-3} (or more) and remained high for

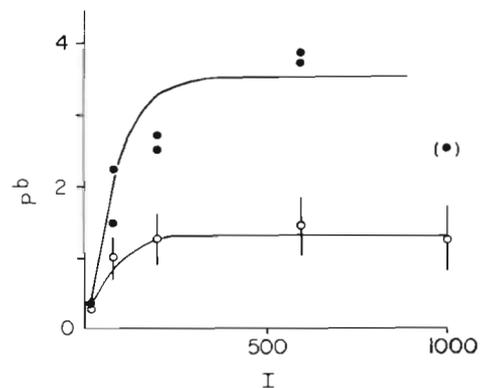


Fig. 4. Comparison of chlorophyll *a*-specific photosynthesis (P^b) vs. irradiance (I) curves for samples taken from beneath the pack ice (open symbols) and a sample taken at Station 36, in the IEZ (closed symbols). Open symbols are means (and error bars are standard deviations) of all experiments ($n = 7$) conducted while in the pack ice. Curves were drawn using parameters derived from Equation (1). P^b has units of $\text{mg C (mg Chl } a)^{-1} \text{ m}^{-3} \text{ h}^{-1}$, and I has units of $\mu\text{Einst m}^{-2} \text{ s}^{-1}$

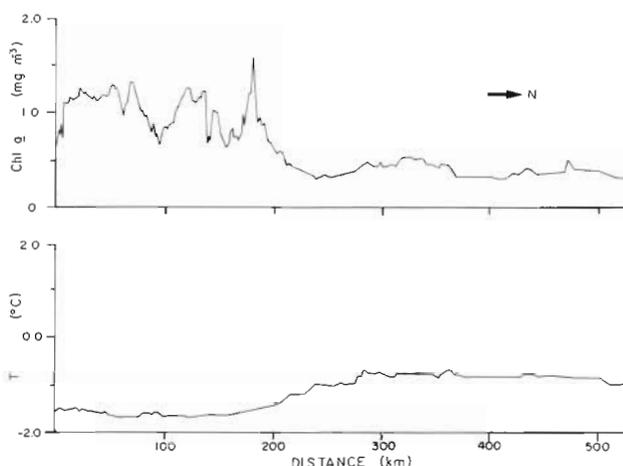


Fig. 5. Near-surface chlorophyll *a* (top) and temperature (bottom) vs. distance plots for the transect beginning upon departure of Station 36 (km = 0). Chlorophyll *a* units are mg m^{-3} , temperature units $^{\circ}\text{C}$. There is a systematic error in the temperature plot of about 0.4°C due to warming of water as it passes through the ship's pumping system

the next 200 km (Fig. 5). Beyond this, temperature increased gradually by 1°C and chlorophyll *a* coincidentally decreased by $\sim 1.0 \text{ mg m}^{-3}$. There is some spatial variability in chlorophyll *a* in the IEZ (Fig. 5), however, the spectrum of this variability shows no significant peaks relative to the temperature variance spectrum. Therefore, both temperature and chlorophyll *a* have a common source of variability (Denman, 1976).

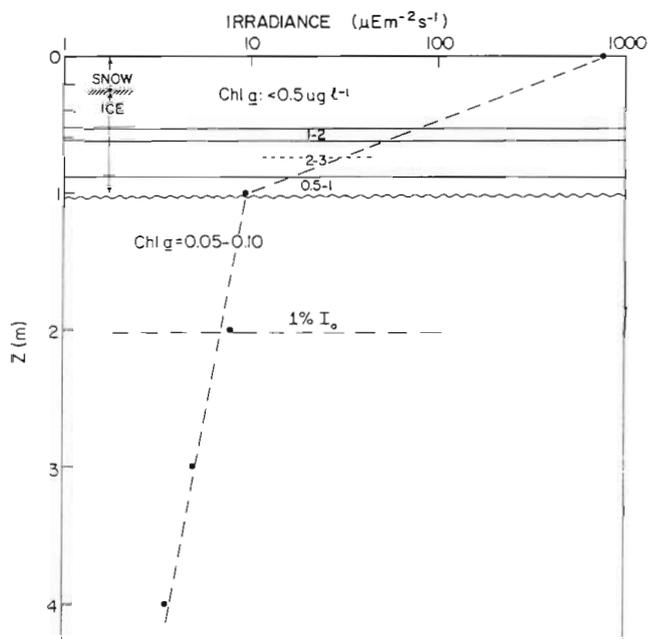


Fig. 6. Generalized schematic of chlorophyll *a* distribution in relation to snow and ice cover, and light attenuation through the ice. Chlorophyll *a* values are approximate; actual values for the cores are presented in Clarke and Ackley (1984)

This source of variability must be a physical process, which does not provide enough persistence to allow spatial variability (due to phytoplankton growth) to develop (Denman et al., 1977; Marra et al., 1982a).

In the area covered by the pack ice, a variable but significant proportion (10 to 30 %) of the biomass of the phytoplankton (as indicated by chlorophyll *a*) is located within the ice column itself. For the Weddell Sea Expedition, Clarke and Ackley (1984) and Burckle (in prep.) treat this complex subject in more detail. In general, chlorophyll *a* concentrations increase in the bottom third of the ice column, much as pictured schematically in Fig. 6. The distribution of chlorophyll *a* correlates positively with the distribution of diatom cells (Clarke and Ackley, 1984). Fig. 6 also shows the attenuation of light through the ice for the one station where we were able to make light measurements. The maximum chlorophyll *a* layer occurs from 1 to 10 % of surface irradiance (assuming exponential decay through the ice). Common species found in the ice include *Nitzschia closterium*, *N. curta* and *Tropidoneis* sp., all pennates, and presumably able to move within the interstices of ice crystals. The other striking feature about the pack ice is the presence of abundant and apparently active heterotrophic populations of bacteria and microflagellates (Marra et al., 1982b). Bacteria, enumerated by the method of epifluorescence microscopy (Daley and Hobbie, 1975), are very large (1 to $3 \mu\text{m}$ in length) compared to bacteria found in the water column beneath the ice.

DISCUSSION

In general, the chlorophyll *a* distributions and the photosynthesis parameters suggest that the phytoplankton populations in the Antarctic during the months of maximum ice extent are largely regulated by the availability of light. A similar conclusion was reached by El-Sayed and Taguchi (1981) for the Weddell Sea in summer. The IEZ exhibited greater water column stability, less ice cover, and anywhere from 2 to 10 times the amount of chlorophyll *a* compared to the water column beneath the pack ice (Fig. 2, 3 and 5). Differences in nutrient concentrations were not of a magnitude to suggest that these might regulate distributions, and differences in temperature were negligible (Table 1; Fig. 2). The increase in P^b_{max} and α (Table 1; Fig. 4) at the ice edge may be interpreted as a physiological response to greater availability of light (Beardall and Morris, 1976; Falkowski, 1980). Although our measurements suggest a euphotic zone (i.e. 1 to 100 % of surface irradiance) extending only 1 to 2 m below the pack ice, and mixed layers to about 100 m, our samples show the populations to have more

typical responses to higher light intensities. There is no severe photoinhibition (cf. Bunt, 1964) and the light intensity at which photosynthesis is maximal is similar to phytoplankton species of temperate and tropical environments (Yentsch and Lee, 1966). Some sea ice diatoms are able to retain viability in darkness (Bunt and Lee, 1972) and other diatom species can remain viable for long periods under extremely low light conditions (Thorne, 1981). At these latitudes (55 to 60°S) there are still about 6 h of daylight at the winter solstice, thus the populations never experience a period of winter darkness. Also, transient leads in the ice would increase the amount of light reaching the under-ice populations and may be a factor in their maintenance.

Significant amounts of chlorophyll *a* are found within the pack ice itself (Fig. 6). This may be part of an active biological community consisting of bacteria, algae and microflagellates that exists in interstices between ice crystals (Marra et al., 1982b). Based on our measurement of light attenuation through the ice at one station, the typical maximum in chlorophyll *a* was found at 1 to 10 % of surface irradiance, which is within the same range of light levels where subsurface chlorophyll maxima are found in stratified water columns (e.g. Cullen and Eppley, 1981).

Much has been written concerning the biological significance of ice edges for all trophic levels (Marr, 1962; Siniff et al., 1970; MacKintosh, 1972; Alexander, 1980; Ainley and Jacobs, 1981; Stirling and Cleator, 1981). It has been hypothesized that the ultimate reason for the importance of ice edges to zooplankton, nekton, mammals, and birds, is the occurrence of enhanced levels of primary production. This has been documented in a few cases (El-Sayed, 1971; Alexander, 1980), but the specific phenomena at ice edges leading to enhanced phytoplankton growth there relative to open water areas are not understood. One possibility is that the algae contained in the pack ice are released upon melting to grow later. This idea is attractive from the standpoint that overwintering in the ice may be part of the seasonal dynamics of Antarctic phytoplankton (Ackley et al., 1979). To our knowledge there is no evidence which would support this idea for the Southern Ocean, although Alexander (1980) found dissimilar populations from sea ice and water column samples in the Bering Sea. Another possibility is that, given the activity of bacteria and heterotrophs in the pack ice (Marra et al., 1982b), the meltwater is suitably 'conditioned' with trace substances and organic chelators (Barber and Ryther, 1969). In support of this hypothesis, Dunbar (1981) reports experiments showing a stimulant effect by melted ice on the growth of laboratory cultures of microalgae. Finally, ice edge blooms may result from purely physical phenomena. Melting pack ice will stabilize the top 5 to 10 m of the

surface layer through input of fresh water, and wind-induced mixing may be reduced near the ice edge, contributing to stabilization of the water column.

During the Weddell Polynya Expedition, we observed localized increases in surface chlorophyll *a* an order of magnitude greater than the values found to the south (in the pack ice region) and 4 times greater than values seaward of the IEZ (Fig. 2 and 5). This localized increase in phytoplankton biomass is associated with greater stratification than further south (Fig. 3) and a decrease in surface salinity which lightens the surface layer by 0.6 sigma-t units (Fig. 2). This is evidence, therefore, suggesting ice-melt freshening of the surface layer as the reason for the IEZ phytoplankton increase. The biomass increase we observe did not appear to be derived from the seed populations contained within the ice. We have no preserved samples from this region; however, *Corethron hystrix* Cestracane and other chain-forming centrics were captured in the zooplankton nets. *C. hystrix* is commonly found in this area of the Weddell Sea (Hart, 1942). This lack of correspondence in water column and ice algae agrees with the finding of Alexander (1980); but we point out that given inadequate knowledge of the temporal dynamics of the ice edge, the importance of seeding with sea-ice algae to the ice edge bloom would be difficult to establish or to rule out. Certainly, *C. hystrix* and other centrics have been found to be present in sea ice (Hart, 1942; Burkholder and Mandelli, 1965).

It may be significant that neither El-Sayed and Taguchi (1981) nor Glibert et al. (1982) found enhanced concentrations of chlorophyll *a* at the summertime ice edge in the Antarctic. It is possible, therefore, that the enhanced phytoplankton activity may be associated with the seasonally receding ice edge and break-up of the winter ice pack. Furthermore, a reduction of wind-induced mixing at ice edges should occur regardless of season. This lends additional circumstantial support to the idea of melt-water stabilization of the water column near ice-edges as the primary factor leading to enhanced productivity of the IEZ. Smith and Nelson (in press) have come to a similar conclusion regarding the distribution of chlorophyll *a* near a receding ice edge in the Ross Sea. The possibility remains that some chemical agent, melted out of the ice, promotes growth of water column phytoplankton (Dunbar, 1981), but this effect should be secondary to any change in water stratification caused by melting. Then too, any organic chelator (for example) will undergo substantial dilution by the surrounding seawater.

In summary, the evidence suggests that the availability of light modulated through water column stratification, ice cover, and melt-water stabilization controls

the distribution of phytoplankton biomass (as indicated by chlorophyll *a*) in the Weddell Sea in late austral winter. The increase in chlorophyll *a* at the IEZ is associated with shallower mixed layers and reductions in surface salinity, both of which would contribute to greater water column stability. Where the water column is covered by ice, the euphotic zone depth is 1 to 2 m, and a significant portion of the phytoplankton (compared to the water column) is found within the pack ice. Although our evidence is indirect, the populations existing in the ice appear healthy and active (Marra et al., 1982b; Clarke and Ackley, 1984).

Since the euphotic zone beneath the pack ice is so shallow, production rates there are probably close to zero. Using the P^b-I curve data, a calculation similar to that of Burkholder and Burkholder (1967) indicates a rate of primary production at Station 36 of 136 mg m⁻² d⁻¹, consistent with rates found by others (Volkovinsky, 1964; Burkholder and Mendelli, 1965; Burkholder and Burkholder, 1967; El-Sayed, 1968). The ice edge bloom, evident from the underway sampling system, reaches 1 to 2 mg m⁻³. If the same P^b-I relation holds there, and allowing for an increase in light attenuation with the higher chlorophyll *a* concentrations (Riley, 1956), rates of production for the ice edge bloom would approach 300 to 400 mg m⁻² d⁻¹. Both the chlorophyll biomass and the primary production estimate for the ice-edge bloom are higher than other values we have found in the literature for similar latitudes and similar times of the year (Burkholder and Burkholder, 1967; Bolter and Dawson, 1982). Clearly, any new estimates of primary production for the Southern Ocean will have to take into account the biological dynamics at the ice edge zone.

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