Water masses and phytoplankton biomass distribution during summer in the Weddell Sea marginal ice zone

Marginal ice
Weddell Sea
Water masses
Nutrients
Chlorophyll

Bord de la glace
Mer de Weddell
Masses d'eau
Sels nutritifs
Chlorophylle

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ABSTRACT

This study - carried out between the Elephant and the Orkney islands - showed that spatial variability in the marginal ice-edge zone (MIZ) was greater than that found in open sea. Salinity and silicate contents point to the existence of two fronts: the first - near Elephant Island - separates the Surface Antarctic Water coming from Drake Passage from the winter water originating in the Weddell Sea. This water is characterized by its high concentrations of nitrate (> 30 μM) and silicates (> 80 μM). The second front - near the South Orkney Islands - undergoes the influence by a less saline water lens (< 34 %), poor in nutrients (N-NO3 < 24 μM) and rich in chlorophyll (> 3.5 mg Chl *a* l^{-1}).

Water masses circulation reveals the existence of a series of convergences and divergences which alternate along MIZ, together with different haline fronts. These fronts limit three differents zones, taking into account the presence of chlorophyll. In zones where the surface layer presents both low salinity and stability with a thickness of about 40 m, chlorophyll contents are rather high - between 1.5 and 5 mg Chl *a*. m^{-3}. On the other hand in the mixing vertical zone, these chlorophyll contents are low (< 0.3 mg Chl *a*.m^{-3}) while the frontal region separating these two zones presents intermediate values and the existence of deep subsurface maximum of chlorophyll. Horizontal variability of integrated values (on the whole of the euphotic zone) is clearly inferior to the one present in surface concentrations.

PON/Chl *a* and POC/PON relations show their minimum levels in the pack-ice fusion water, as an effect of the high photosynthetic activity.

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RÉSUMÉ

Étude de la répartition des masses d'eau et de la biomasse phytoplanctonique en période estivale (été 1988-1989) dans la zone marginale de glace en mer de Weddell

Conduite entre les îles Eléphant et Orkney, cette étude a montré que la variabilité spatiale dans la zone marginale de la glace (MIZ) était aussi élevée que celle rencontrée en mer ouverte. Salinité et teneur en silicates soulignent l'existence de deux fronts ; l'un, situé près de l'île Elephant, sépare l'eau superficielle antarctique provenant du passage de Drake de l'eau d'hiver de la mer de Weddell caractérisée par de très fortes concentrations en nitrates (> 30 μM) et, surtout, en silicates (> 80 µM). L'autre front, dans les parages des îles Orkney du sud, délimite la zone d'influence d'une lentille d'eau moins salée (< 34), appauvrie en sels nutritifs ($N\text{-}NO_3 < 24$ µM) et, parallèlement, riche en chlorophylle (> 3.5 mg Chl *a* l^{-1}).

La circulation des masses d'eau souligne la présence d'une série de convergences et divergences alternées le long de la MIZ, accompagnées de différents fronts halins. Ces fronts délimitent trois zones qui diffèrent par leur richesse en chlorophylle. Dans la zone où la couche superficielle est peu salée et stable sur une épaisseur d'une quarantaine de mètres, les teneurs en chlorophylle sont assez élevées pour l'océan austral: entre 1,5 et 5 mg Chl *a* l^{-1}. Par contre, dans la zone de mélange vertical, les teneurs sont basses (0,3 mg Chl *a* l^{-1}) alors que la région frontale séparant ces deux zones présente des valeurs intermédiaires et se caractérise par l'existence d'un maximum «profond» de chlorophylle. La variabilité horizontale des valeurs intégrées sur l'ensemble de la couche euphotique est évidemment inférieure à celle des teneurs de surface. Reflet de l'activité photosynthétique élevée, les rapports NOP/Chl a et COP/NOP atteignent leur minimum dans l'eau de fusion du pack.

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INTRODUCTION

The border zone which separates the waters flowing northward out of the Weddell Sea from those in the Southern Scotia Sea has been referred to as the Weddell-Scotia Confluence (WSC) by Gordon (1967). Several water masses are found in the vicinity of Elephant Island. Antarctic Surface Waters flowing through the southern part of the Drake Passage are modified on the shelf of the South Shetlands (Clowes, 1934; Anonymous, 1983) and glacial melting (Sarukhanyan and Tokarczyk, 1988) cools the near-surface layer. Surface waters flowing through the Bransfield Strait also undergo transformation, either through mixing with Weddell Sea waters or as the result of processes which take place on the shelf of the Antarctic Peninsula (Clowes, ibid.; Gordon and Nowlin, 1978; Tokarczyk, 1987). Near Elephant Island, these water masses, already partially modified, meet Weddell Sea Surface Waters which flow from the southwest. However, the mixing of all these types of waters is restricted by the southern ridge of the submarine Scotia Arc which forms a barrier there [the WSC zone (Wüst, 1926; Deacon, 1937)], consisting of relatively homogeneous water with Circumpolar Warm Deep Waters on one side and Warm Deep Water of the Weddell Sea on the other (Gordon, 1967; Gordon *et al.*, 1977; Patterson and Sievers, 1980). This zone stretches from the region of the South Shetlands, through the Elephant and South Orkney islands to the South Sandwich Islands, meeting the Bellingshausen Sea Front, which has been described by Model (1958). Between the Elephant and South Orkney islands, the boundaries of this zone are marked by a thick, homogeneous water column, in which water temperature remains constant at depths ranging from several hundred metres to several kilometres (Stein, 1981; Anonymous, 1983). The formation of this column seems to be associated with intensive thermohaline convection supported by the processes of vertical mixing caused by lateral friction between flowing water masses and the submarine ridge (Deacon and Foster, 1977; Patterson and Sievers, 1980). These factors give rise to the presence of large quantities of nutrients in the photic layer, but it also generates large water masses with low stability, great horizontal and vertical movements that prevent phytoplankton from taking nutrients.

In regions where the ice edge is present, the most widely accepted hypothesis advanced to account for primary production is the beneficial effect of pack-ice melting which generates physical stability to prevent the loss of cells at greater depths and maintains the growth of phytoplankton blooms in a high-light, high-nutrient environment (Sakshaug and Holm-Hansen, 1984; El-Sayed, 1984; Smith and Nelson, 1985; Nelson and Smith, 1986). Melting may also create a pathway for inoculation in the water of plankton which has been initially developed in the interior of the pack-ice (Garrison and Buck, 1985; Garrison *et al.*,1987).

Although most studies of the marginal ice zones [MIZ (Smith and Nelson, 1985; Nelson *et al.*,1987)] have addressed spatial variability in sections perpendicular to the ice, little is known of the small-scale variability within these zones. The stability generated during the ice-melting favours the increase of photosynthetic activity in the MIZ, but it is to be expected that this effect will not be uniform. Sullivan *et al.* (1988) show an important spatial variability in pigment concentration in the MIZ obtained by ocean colour (CZCS).

The aim of this paper is to study the main physical factors that determine the dynamics of small-scale water masses and their relation to the pigment and nutrient distribution. Simultaneously to this experiment in the MIZ, another larger study was carried out on board R/V *Polarstern* in repeated sections crossing the ice edge.

MATERIAL AND METHODS

Between 29 December 1988 and 9 January 1989, on board R/V *Professor Siedlecki*, measurements of water temperature, salinity, and dissolved oxygen were made at 29 sta-

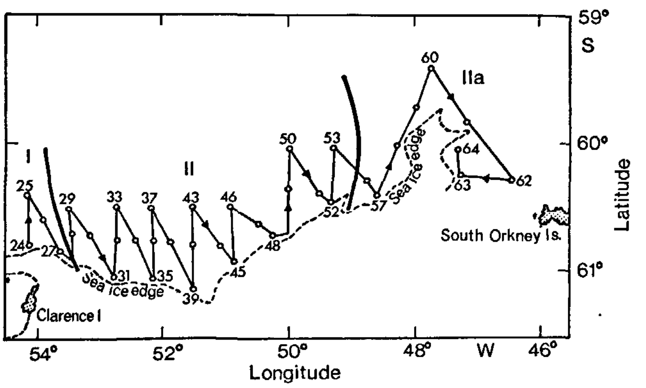


Figure 1

Position of stations and ice-edge during the cruise of R/V Professor Siedlecki *29 December 1988 to 9 January 1989. The different types (I, II and II a) of seawater are indicated. Type I is Surface waters flowing through Drake Passage and Bransfield Strait, type II is Weddell Sea Winter Water, type II a is Weddell Sea Water, summer modification.*

tions located within a 40-mile zone off the ice edge between Elephant Island (54.5° W) and the South Orkney Islands [46.5° W (Fig. 1)]. Profiles of conductivity, temperature and dissolved oxygen were completed with a Neil-Brown CTD-O_2 probe between 0 and 1 000 m. The Neil-Brown probe was calibrated with reversing thermometers (Gohla-Kiel, Germany) and a Plessey Model 6230 N Laboratory salinometer. The dissolved oxygen sensor was calibrated using the modified Winkler method (Carritt and Carpenter, 1966).

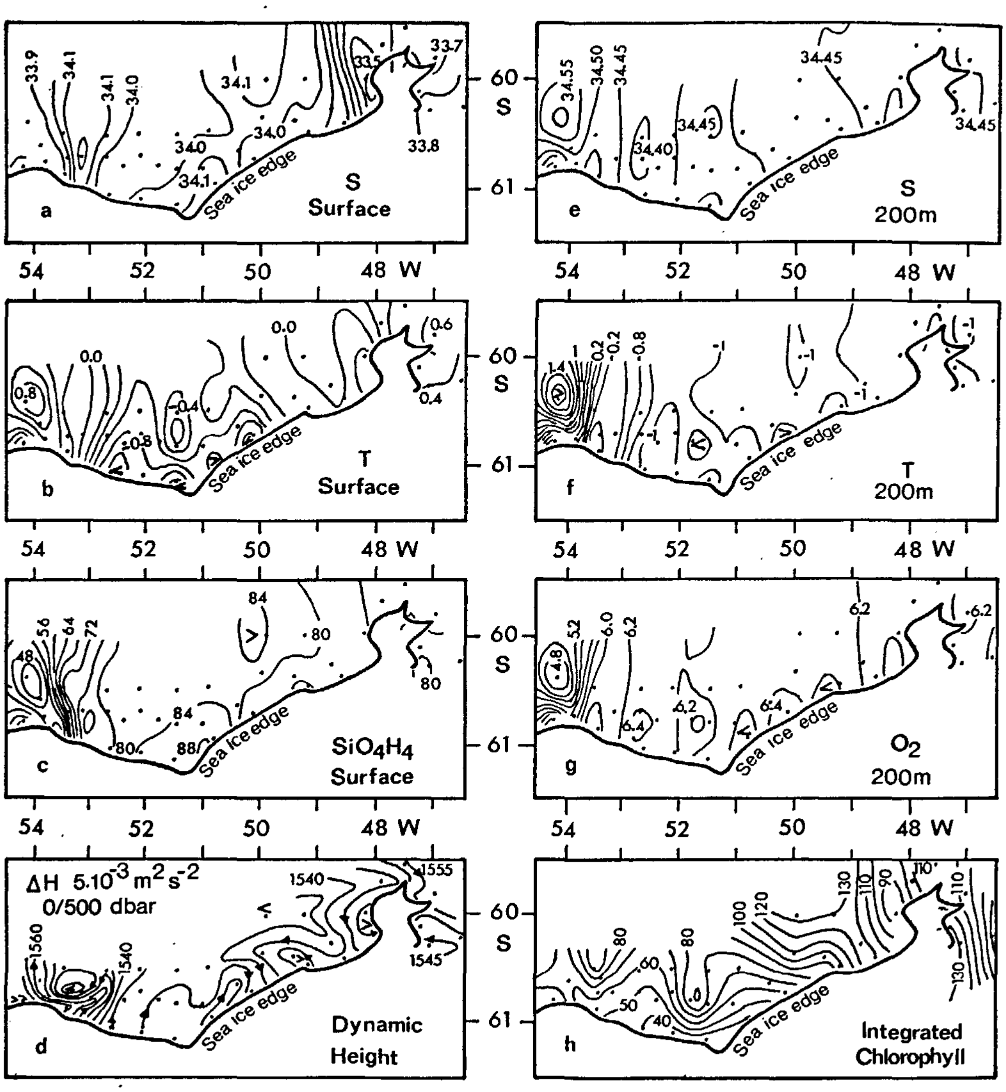
Water samples were collected at depths of 0, 10, 20, 30, 40, 50, 75, 100, 150 m and silicate, nitrate, pH, alkalinity and chlorophyll were analysed. Nutrients were promptly determined by colorimetric methods, using a Technicon autoanalyser. For determining the content of silicates a modified Grasshoff method was used, in which an isomer of silicomolybdic acid is reduced with ascorbic acid to an intensely blue complex (Hansen and Grasshoff, 1983). Nitrate was determined after reduction to nitrite in a Cd-Cu column, using a classical Griess reaction (Mouriño and Fraga, 1985).

A "Metrohm" E-654 pH meter, with a Ross Orion 81-04 electrode calibrated with 7.413 NBS buffer, was used to determine pH promptly. Temperature was measured at the same time with a Pt-100 resistance thermometer which allows the correction of the pH according to temperature. All pH values refer to 15°C (Pérez and Fraga, 1987).

Fluorescence measurements were made with a Turner Design 1000 R fluorometer. Samples had to be adapted to

Figure 2

Horizontal distributions of: surface salinity (a), surface temperature (b), surface silicates (c), dynamic heights (d), salinity at 200 m (e), temperature 200 m (f), oxygen (g) at 200 m, and the integrated chlorophyll down to 150 m.



darkness and lab temperatures for 20 minutes (Falkowski and Kiefer, 1985). Three types of measurements were made: *in vivo* fluorescence (F_v); maximum fluorescence after adding DCMU (F_d); and the fluorescence after adding 1N HCl. The fluorescence ratio ($F_d/F_{d\,+\,HCl}$) was used as the phaeophytin index. Chl *a* was estimated from F_d readings. For calibration, 100 ml of water samples in which fluorescence had been measured, were filtered through 2.5 cm Whatman GF/F filters and the chlorophyll extracted with 90 % acetone. The fluorescence of the extracts was measured with the same instruments and the chlorophyll concentrations corrected for phaeopigments (Yentsch and Menzel, 1963; Holm-Hansen *et al.*, 1965). The correlation coefficient between the Chl *a* values calculated and the F_d reading was 0.98 allowing us to obtain a factor relating the two measurements.

For the analysis of particulate carbon and nitrogen, two litres of water were filtered through Whatman filters GF/F 25 mm diameter. The analyses were carried out in a Perkin Elmer 240 Elemental Analyser, following Fraga's technique (1976). The blank values of filters are 0.8 µmol C and 0.06 µmol N, and the reproducibility of the method are ± 0.1 µM C and ± 0.02 µM N, respectively.

RESULTS

Water mass distribution

Surface distribution of salinity and silicates shows two front zones situated approximately along 53.5 and 49.5°W respectively, where the existence of strong gradients permits to distinguish three types of water masses (Fig. 2). The fronts situated 53.5°W separates westwards two water types: the first, rather warm (type I, 0.4 to 0.8°C) with low salinity and silicate content (36 to 63 µM), and the second, cold (type II, - 0.2° to - 1.0°C), with high salinity (34.00 to 34.45) and high silicate content (> 80 µM) situated in the central and east part of the region studied. The other front defines a region eastwards 49.5°W occupied by a water layer (type II *a*) of approximately 40 m, less saline (33.4 to 33.9) and warmer (0° to 0.6°C) than the water situated in the central part, westwards from this front (type II).

Type II *a* water is a summer modification from type II (Winter Weddell Water -WWW) due to the ice melting. The high silicates level is a clear evidence that Weddell Sea is the source of type II and type II *a*, while the properties of type I waters suggest that they flow along the Shetlands through the southern areas of Drake Passage and Bransfield Strait (Tokarczyk, 1987).

Circumpolar Warm Deep Waters (CWDW, type III, Fig. 2) were found 200 m depth with a temperature approaching 1.8°C and salinity of 34.6. The boundary of this type of waters show WSC position, well-delimited by its strong gradients of silicates (Szpiganowicz *et al.*, 1985; Nelson *et al.*, 1987).

In the TS diagram (Fig. 3) we have typified the four types of waters, taking into account the different levels of silicate content.

The dynamics of the waters masses do not show a significant correspondence with the form of the ice edge (Fig. 2). But we can clearly distinguish westwards the baroclinic gradients associated with WSC hydrographical variability. The rest of the area is characterized by several cyclonic and anticyclonic meanders that alternate in transversely crossing the ice edge.

We have characterized two opposed hydrological structures from a vertical distribution of salinity along a transect parallel to the ice edge that goes through maximum and minimum dynamic heights, from 51.5° to 47°W and that crosses the 49.5°W saline front (Fig. 4). The central part of the studied area (stations 39 to 45) is occupied by homogeneous water (type II), while in the East part (stations 54, 58 and 61) there is a water lens presenting low salinity, this due to ice melting. In this type of saline fronts, bodies of water resulting from lateral mixing sink under the less saline layer. The haline front that separates types 2 and 2 *a* is divided here in two fronts associated with isohalines 33.95 and 34.15 respectively. The first and strongest front delimits the west boundary of type II a at 48.5°W. The other one, situated at 50.3°W between stations 45 and 48 is weaker, but reaches more depths. Currents obtained from dynamic heights (Fig. 2) in both fronts run southeastwards. Each front presents a divergence area (D) and a convergence one (C) on the right and left sides respectively of the southeastward currents. A local downwelling is produced between both front and convergence area.

Chlorophyll and nutrient distributions southeastward from WSC

Different hydrological structures generate different distributions of Chl *a*. Maximum values are always found in the surface. However, relatively high values of Chl *a* (< 2 mg.m^{-3}) are located only in the water lens of type II a (Fig 4); under it, chlorophyll values decrease quickly between 40 and 60 m. Conversely, in an homogeneous water

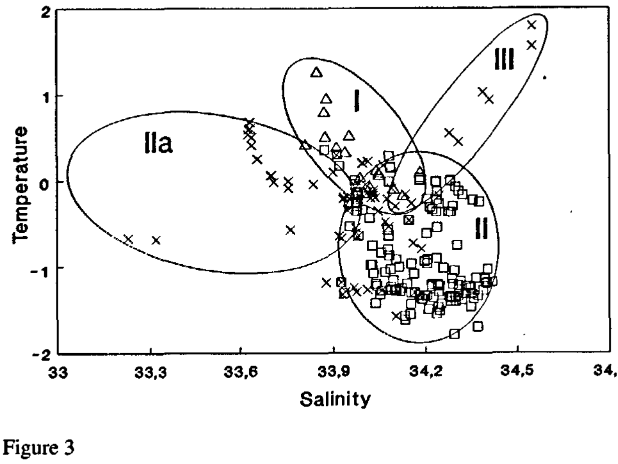


Figure 3

T-S diagram of all dates above 150 m. The symbols show differents level of silicates (triangles < 63, crosses > 63 and < 82, and squars > 82 µM). The four types are summarized taken into accounts both T-S relationship and silicates levels.

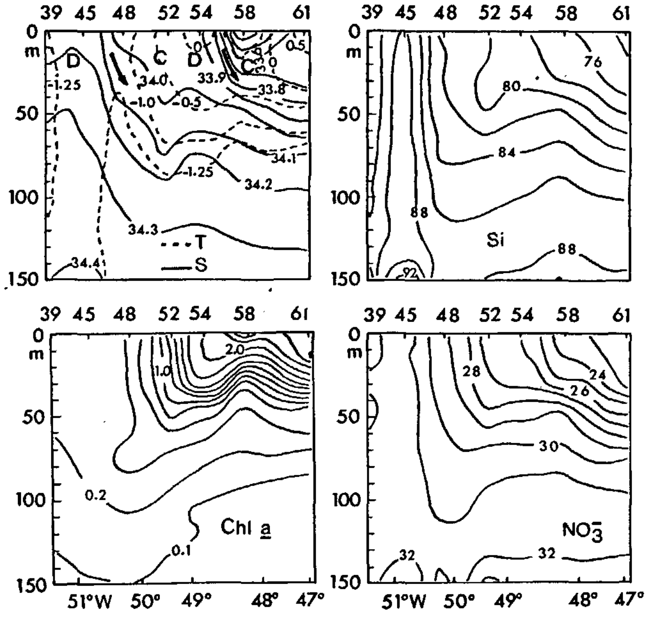


Figure 4

Vertical sections of salinity, temperature, chlorolphyll a *(mg.m*$^{-3}$*), silicates (µM) and nitrates (µM) in a transect close to edge-ice between stations 39 and 61. The D and C indicate the divergence and convergence areas, respectively.*

body (type II), there are low and constant ones (< 0.3 mg.m^{-3}), with a minimum values of integrated Chl *a* down 150 m (INTCHL) of approximately 40 mg.m^{-2}. A lateral gradient of Chl a between the two fronts at stations 48 and 54 can also be observed but the values of the INTCHL are not very inferior to those existing in low salinity lens. So, westwards 50°W, the distribution of INTCHL shows little variability (from 100 to 130 mg.m^{-2}), with the highest values at station 61.

Chl *a* profiles (Fig. 5) show a constant decrease on the surface layer and also an increase in Chl *a* levels in the subsurface layer from type II a water (station 52) to type II water (station 39). Between the two haline fronts (stations 52 and 48), the water column has lower Chl *a* levels than those found in type II a water, but fluorescence ratios ($F_d/F_{d+HCl} > 2.3$) and fluorescence quantum yield - down to 50 m - [$(F_d\text{-}F_v)/Fv$ of 1.4; Kolber *et al.*, 1990; Falkowski *et al.*, 1991] suggest the sinking of healthy phytoplankton from the surface layer near the convergence at station 52. This behaviour also agrees with the slight decrease of nutrients at station 48 below 50 m.

Nitrate and oxygen distribution strongly correlates with the haline one (r = 0.89 and 0.85 respectively). So, the mixing of water controls most part of the nutrient variability. However, between stations 45 and 48, nitrate and oxygen gradients reach lower depths than the saline ones, in concord with Chl *a* in these stations at 70 m. The distributions of pH_{15} (not shown) and silicate have a very similar behaviour, with the correlation coefficients of 0.84 and 0.83.

If photosynthetic activity did not exist and knowing that type II a is a modification of type II, the changes in nutrient concentration would be only caused by the water dilution of the fusion of ice. However, there is a significant decrease of NO_3 of approximately 10 µM in the surface layer west of station 52 (decrease of silicate and increase of oxygen and pH also occur), and the amount of Chl *a* does not seem to balance this depletion. Taking into account that approximately 1 µmol of NO_3 consumed produces 1.4 mg of chlorophyll (Dortch, 1987; Fraga and Perez, 1990), Chl *a* should be higher than 12 mg.m^{-3}. This lack in the balance can be understood if we see the great differences in a time scale. Nitrate consumption is much more conservative than Chl *a* as it is reflected in the total amount of nitrate eliminated during the ongoing growth season (Jennings *et al.*, 1984).

On the other hand, Chl *a* in the WSC is inferior to 1 mg.m^{-3}, showing nutrients distribution and also high covariance with salinity with the exception of a few samples of CWDW, that showed low oxygen values (4.6 ml.l^{-1}) and high nitrate ones (38 µM).

Composition of particulate organic matter

Figure 6 shows the relation between PON and the values of corrected chlorophyll by phaeopigments measured by fluorescence. The data shows a good correlation ($r^2 = 0.87$) with a slope of 1.05 ± 0.05 µg Chl *a* by µmol PON. However, the points seem to distribute themselves into two groups, probably related to different populations in the two water bodies. High Chl *a* values are located in type II a water, with salinities lower than 33.9 (Fig. 4). They represent a regression slope of 1.28 ± 0.23 g Chl *a* by mol PON (carbon: Chl *a* ratio about 42), close to that

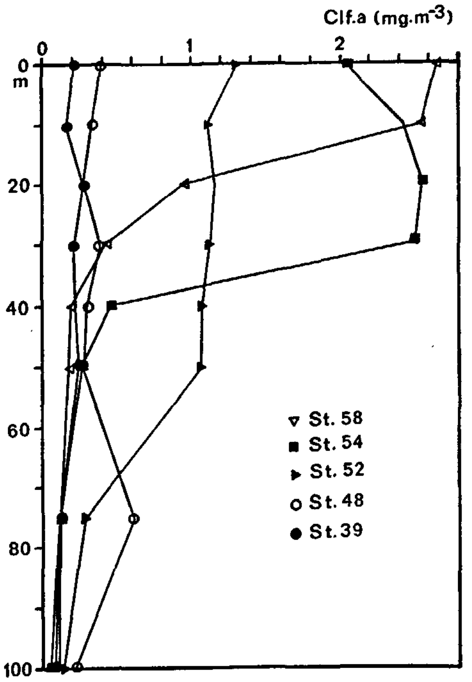


Figure 5

Vertical profiles of chorolphyll a (mg.m^{-3}*) corrected by phaeopigments in the stations (39, 48, 52, 54, and 58).*

published by Dortch (1987), which gives a ratio of 1.8 µg Chl *a* per µmol of proteic nitrogen, equivalent to 1.44 µg of Chl *a* per µmol PON. At salinities higher than 33.9, in type II (WWW, low PON and Chl *a* values are found, and the slope drops to 0.52 ± 0.04 g Chl *a* by mol-PON (carbon: Chl *a* ratio about 143), this suggesting the presence of particulate material without chlorophyll. In a first approximation the value of the y-intercept in these regressions is an estimation of the amount of detritus, or at least non-chlorophyllous particulate material. At stations showing moderate Chl *a* levels, the y-intercept is about 1.2 µmol PON.l^{-1} (about 5.5 µmol POC.l^{-1}), whereas at stations dominated by type II water and having low Chl *a* , the y-intercept is about 0.1 µmol PON.l^{-1} or 0.6 µmol POC.l^{-1}.

The C:N ratio shows (Fig. 6) a similar behaviour. Two groups are clearly differentiated by their PON contents and their C:N ratios. In this case, high PON values show a mean C:N ratio of 4.5. This indicates the existence of phytoplankton growing vigorously. On the other hand, the low POC levels associated with samples obtained in the type II water with low Chl *a* and low phaeophytin indices, give a C:N slope of 6.2.

All these data indicate that two differents sub-ecosystems coexist in the MIZ with distinct particulate matter compositions, following the same pattern than that of the nutrient distribution.

DISCUSSION

During *Biomass IV* cruise, both thermohaline distribution and the dynamic structure observed through dynamic topography suggest the existence of important advective vertical and horizontal processes affecting the surface layer, giving rise to a small-scale strong variability all along MIZ. Here we found zones of high stability associated to the pack-ice melting and also zones with high vertical homogeinity, together with alternating transverse saline fronts at the ice edge.

This behaviour contrasts in some way with the general model obtained from the study of transverse sections where the pack-ice and the open sea dynamics are compared. Results obtained during *Epos II* (26 November 1988 to 4 January 1984) in four tranverse sections at the ice edge showed, on the whole, little spatial variability from the ones described here (Goeyens *et al.*, 1991; Cederlöf *et al.*, 1989). During *Biomass IV*, salinity minimum associated with ice-melting were less than those observed during *Epos* Leg 2, however, water columns of great homogeinity were found in *Biomass IV* at the very ice edge.

Jacques and Panouse (1989) show different patterns of pigment distribution in three following regions during the *Epos* Leg 2 : WSC, MIZ and Weddell sea. These patterns had been formerly described in other Antarctic areas by several authors (El-Sayed and Taguchi, 1981; Smith and Nelson, 1985). Here the same patterns in Chl *a* have ben observed in MIZ separated by three saline fronts. And also the highest contents of both Chl *a* and INTCHL were found in the low-salinity lens (El-Sayed, 1984). However, Chl *a* profiles with intermediate values stretched in relatively deep layers, with high values of INTCHL have also been observed.

The observation of pigment distribution and ice retreat processes followed by satellite images also shows a strong variability all along MIZ, where a complex hydrographical field strongly affects phytoplankton growth and accumulation (Sullivan *et al.*, 1989). It can be expected that this strong dynamics gives rise to an important vertical variability implying different vertical distributions of pigments, as the ones described here, and that do not correspond directly with the surface distribution.

The distribution of the nutrients here studied follows the general behaviour already described in previous papers (Nelson and Smith, 1986; Treguer and Jacques, 1992). But the highest variability is found in parallel sections in the ice-edge, as it happens with hydrographical structure, with high covariance with the saline field. This high covariance cannot be diretly explained by the dilution of WWW (type

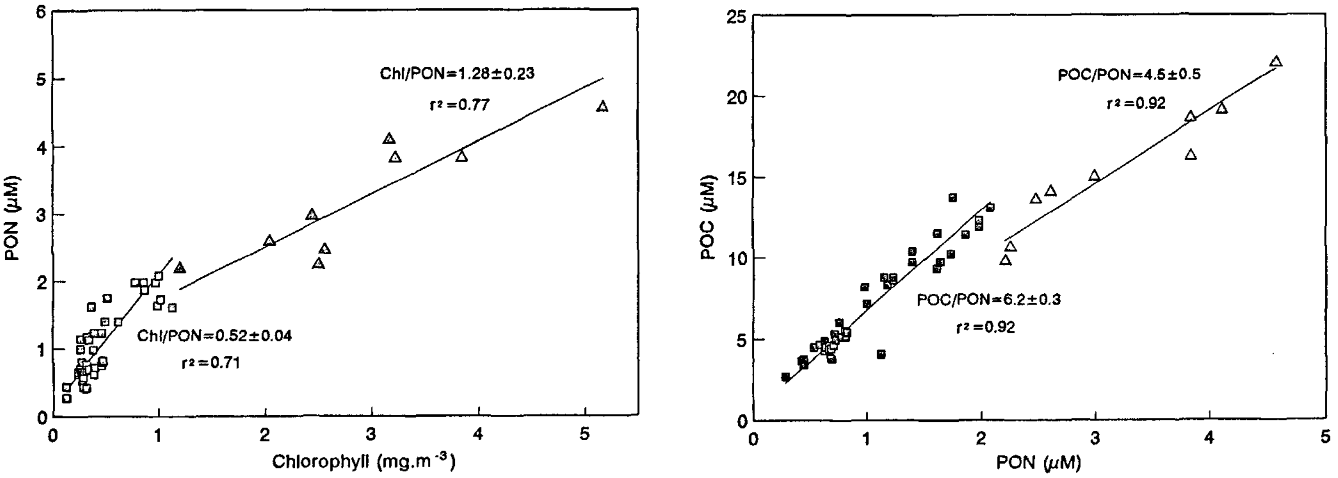


Figure 6

Relation between corrected chlorophyll, PON, and POC in suspended organic matter in seawater.

II) with the meltwater, since the dilution factor obtained through salinity does not reach 4 % and the nitrate input from the ice is practically very low (< 1 µM).

These nitrate decrease, together with the consumption of other nutrients (silicate, inorganic carbon followed by pH increase) seem to take place in the growing season in low salinity lenses. Jennings *et al.* (1984) and Goeyens *et al.* (1991) applied a similar reasoning for the study of nutrient distribution in Weddell Sea, near the ice edge. Although other nitrogen sources have not been studied during *Biomass IV*, nitrate is the main source of inorganic nitrogen consumed by phytoplankton in the MIZ during the first bloom (Smith and Nelson, 1990; Goeyens *et al.*, 1991). Small-scale studies are necessary to determine if the consumption of nutrients is carried out in the water in contact with the pack-ice by the ice-algae, or in the water column by the phytoplankton once the pack-ice is melted down. The high correlation between saline and nutrient distribution in the MIZ could be due to the consumption carried out by phytoplankton in the water column if photosynthetic activity had also high correlation with salinity. Conversely, a model with strong depletion of nutrients taking place in the sea water in contact with the pack-ice during its melting, and caused by ice-algae activity, would be better adapted to the behaviour observed between nutrients and salinity.

The amounts of particulate matter and the different relations between Chl *a*, POC, and PON concentrations are closely connected to the physical environment in which they were observed. In low salinity lenses, the low C:Chl *a* and C:N relations indicate that physiologically conditions are favourable to phytoplankton which has taken in the biggest fraction of the particulate matter. A very similar behaviour was found by El-Sayed and Taguchi (1981) in two regions of the Weddell Sea, with different hydrological conditions (Table). They show relations of C:Chl *a* and C:N of 35 and 7 respectively in areas with surface euphotic layers (20.3), whereas those relations rose to 416 and 9.1 in areas of thick ones (57 m).

In the MIZ of Weddell Sea, Nelson *et al.* (1987) observe during the spring similar values of POC, PON and chlorophyll and also low values in the relation C:Chl *a*. However, the C:N relation is higher than that obtained here through lineal regression. At the end of summer in the MIZ of the Western Weddell Sea, Nelson *et al.* (1989) gave POC, PON, and Chl *a* values which concord with those found here in the bodies characterised as Winter Weddell Water (type II). Besides, they have obtained a detrital C of 1.5 µM, slighly superior to the one estimated here. This suggest that homogeneous water bodies found at MIZ in spring or at the begining of summer are not very different from those found at the end of summer, once the pack-ice has been melted down.

During a strong bloom in the MIZ of Ross Sea, Nelson and Smith (1986) obtained low C:N ratios, slightly superior to those shown here (Table). Conversely, in the Antarctic Indian Sector, Tréguer *et al.* (1988) obtained lower PON and POC concentrations with high C:Chl *a* ratios.

Table

Mean values of selected phytoplankton biomass in three marginal ice zones of the Southern Ocean.

Region	**Chl *a*** mg.m^{-3}	**POC** µM	**PON** µM	**C:Chl *a*** g:g	**C:N** mol:mol
[1] Weddell February-March 1977					
North and Central	0.06	2.2	0.25	416	9.1
Southern	1.56	4.4	0.63	35	7.0
[2] Weddell-Scotia					
November 1983	4.0	10.6	1.5	31.8	7.1
[3] Western Ross					
January-February 1983	2.9	33.2	5.6	138	5.9
[4] West Weddell					
March 1986	0.38	3.6	0.46	114	7.8
[5] Indian Sector					
January-February 1984	0.21	7.2	0.97	410	7.3
[6] Weddell 1989					
Meltwater	3.12	16.2	3.33	43	4.9
Weddell water	0.47	7.1	1.15	120	6.2

[1] El-Sayed and Taguchi (1981).
[2] Nelson *et al.* (1987).
[3] Nelson and Smith (1986).
[4] Nelson *et al.* (1989).
[5] Treguer *et al.* (1988).
[6] This work.

Acknowledgements

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