KERFIX, a time series station in the Southern Ocean: a presentation.

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Abstract

Between January 1990 and March 1995, the research project KERFIX proposed the first regular multiyear acquisition of parameters related to the carbon cycle in the Southern Ocean at a time series station located at 50° 40′ S - 68° 25′ E, 60 miles southwest off Kerguelen Islands. The objectives of KERFIX are 1) to monitor the ocean/atmosphere CO_2 and O_2 exchanges, to understand which processes govern these exchanges 2) to observe and interpret the seasonal and interannual variability of the production, flux, decomposition and dissolution of carbon and associated elements at this location. In addition, micropaleontological studies describe the present and past flux dynamic in this oceanic area, in order to improve the knowledge of the transfer functions of some oceanographic proxies.

This paper presents a survey of the KERFIX program: scientific objectives, organization of the field operations and some main results obtained since the beginning of KERFIX program, as well as the results of the temporal evolution of hydrological, chemical and biological parameters.

Résumé

Entre janvier 1990 et mars 1995, le projet de recherche KERFIX a proposé le premier suivi régulier pluriannuel de mesures de paramètres liés au cycle du carbone dans l'Océan Austral, à une station fixe située dans le quart sud-ouest de Kerguelen (50° 40S -68°25 E). Les objectifs de ce programme sont 1) de paramètrer les échanges d'oxygène et de gaz carbonique entre l'océan et l'atmosphère afin de comprendre les processus qui gouvernent ces échanges et 2) d'observer et d'interpréter les variations saisonnières et inter annuelles de la production et de la décomposition du flux de carbone et d'éléments associés à ce site. De plus, une étude micro paléontologique permettra une documentation actuelle et passée de la dynamique du flux de matière à cette station, ce qui permettra d'affiner notre connaissance de certains proxis océanographiques.

Cet article présente une vue d'ensemble du programme, de l'organisation du travail de collecte et d'analyse et quelques résultats acquis depuis le début de sa mise en oeuvre, tels que des données temporelles de paramètres physiques, biologiques et chimiques.

Introduction: JGOFS scientific objectives and time-series stations

One of the most important goals of JGOFS is to improve our estimations of how much the ocean takes up the carbon dioxide (CO_2) released into the atmosphere through human activity and of the processes that control this flux. A recent review of oceanographer's current comprehension and quantification of this flux, underlines our ignorance about the detailed behavior of the solubility and biological "pumps" that move a portion of the carbon that crosses the air-sea interface from the surface waters to depth. In addition, the amplitude of seasonal variations of carbon fluxes relative to that of the anthropogenic signal makes sampling difficult (Sarmiento, 1995).

To understand the mechanisms governing the carbon fluxes, two measurement approaches are possible. The first consists in organizing research cruises in characteristic biogeochemical provinces and in different seasons to constrain the seasonal variability. Such studies allow to understand the processes at play and to quantify their relative importance. The second approach involves the continuous acquisition of parameters from one sampling location in the ocean; it is less frequently applied because of the logistical overheads.

Yet, time-series' observations conducted over many years are essential to our understanding of seasonal, interannual and longer-term trends and cycles. Indeed, long-term monitoring allows to evaluate the seasonal and interannual variations in the key parameters used to estimate: i) the surface gas flux (CO_2, O_2) at the ocean/atmosphere interface, ii) the primary production and transient particle fluxes in the water column, and iii) their evolution at depth. Garçon *et al* (1992) estimated that a minimum of 24 measurements per year is required to constrain the average air-sea CO2 flux at station P. Nevertheless, calculated averages derived from monthly measurements allow to estimate annual fluxes with a better precision than with data acquired during a one-off research cruise. The key parameters describe the physics, the biology and the chemistry of the water column; the data acquired over many years, in addition to processus data aquired in biogeochemical provinces, will also allow to calibrate coupled physics/chemistry/biology models in one dimension. The resulting better understanding of the 1 dimensional processes occurring in the water column will make easier the development of such coupled models in 3 dimensions.

One of the first multi-year time series station was the Ocean Weather Station P, located in the middle of a large horizontal expanse of the sub-arctic North Pacific oceanic body. It was not planed in the framework of JGOFS and the sampling strategy will not be detailed here; it was focused on surface

Table 1: Parameters analyzed as part as KERFIX program. For each of them the duration of the acquisition, the places where they are analyzed and the laboratory in charge of the given parameter are recalled (the addresses corresponding to the logos are in the title page).

Parameter	Collection duration	Analytical Place	Laboratory
T,S,P,O_2,CO_2,Alk	1990-1993	Kerguelen	LPCM (Paris)
T,S,P,O_2	1994/95	Kerguelen	UMR 39 (Toulouse)
NO_3	1992-95	Metrop.	UBO (Brest)
Si,P,NH_4	1992-95	Kerguelen	UBO/UMR39
Chla	1992-95	Ker/Metrop.	Arago (Banyuls)
Bacterial	1992-95	Ker/Metrop.	Arago
Zoo. (biomass)	1992-95	Ker/Metrop.	Arago
Zoo(grazing)	1993-95	Ker/Metrop.	Arago
Incubation N	1992-95	Ker/Metrop.	ANCH (Brussels)
Incubation Si	1992-95	Ker/Metrop.	UBO (Brest)
Bio and litho Si	1992-95	Ker/Metrop.	UBO
Filtered particles	1992-95	Ker/Metrop.	ANCH
$\delta^{13}C$	1992-1993	Metrop.	CFR (Gif/Yvette)
Currentmeters	1993-1995	Metrop.	LOP (Paris)
Mass Flux	1993-95	Metrop.	*UMR39 /IAEA-MEL (Monaco)*
SEM			*LMCE (Gif/Yvette)*
Pigments			*Arago*
Fecal pellets			*IAEA-MEL*
Micropaleontology			*CRESO /CFR (Bordeaux/Gif)*
Radioinuclides			*CFR*
CIP, COP, NP			*IAEA-MEL*
PP			*UBO*
Si, Sibiogenic			*UBO*
Al, Ca, Sr, Ba, $\delta^{13}C$ et $\delta^{15}N$			*ANCH*
Trace elements, Nd			*UMR 39*

meteorology, *in situ* hydrography, chemistry and biology (Anderson *et al.*, 1977; Tabata, 1979; Tabata, 1965).

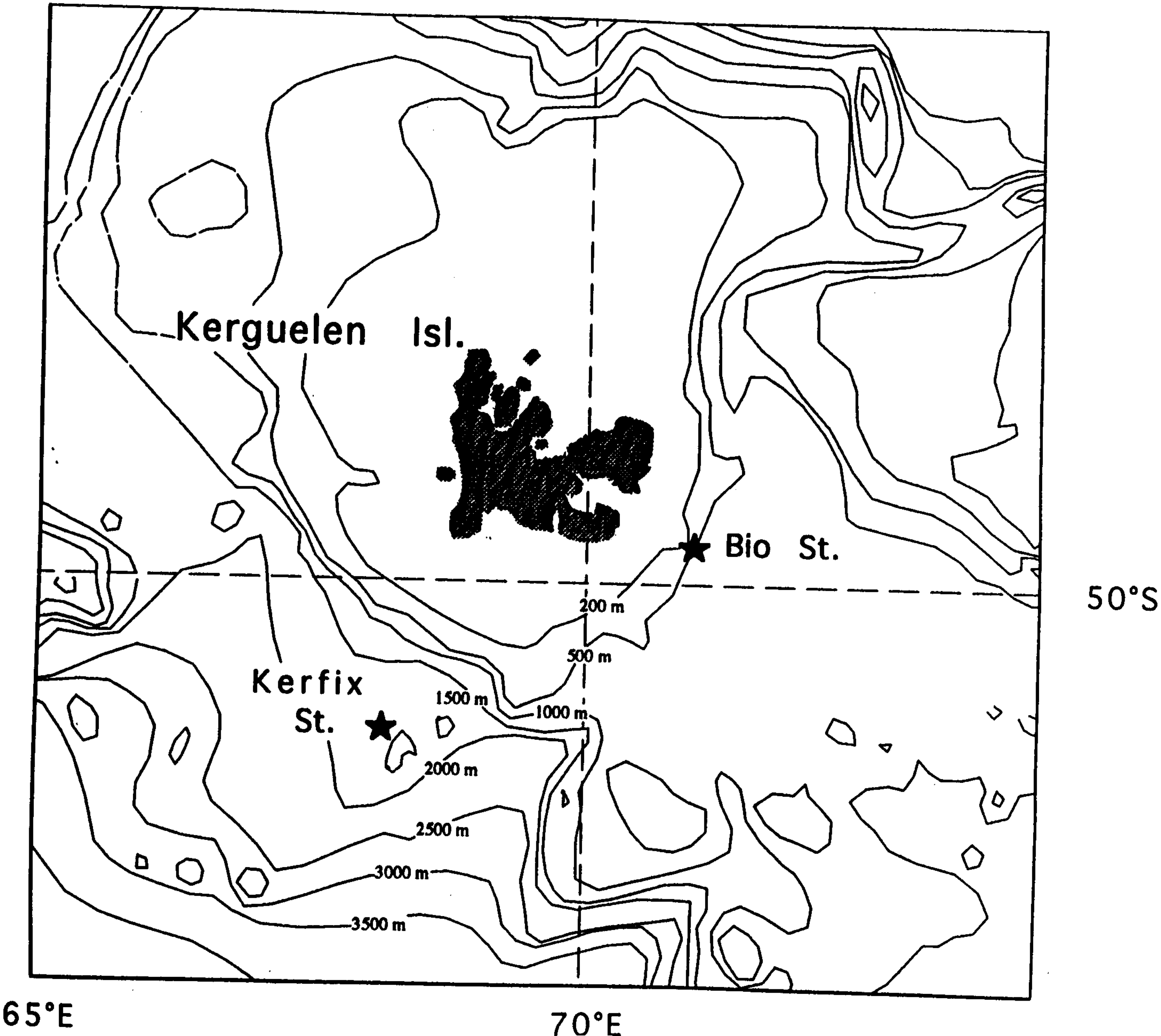
In the framework of JGOFS, several time-series' stations have been developed or reinforced, the most famous being the Hawaii Ocean Time-Series (HOT) and the Bermuda Atlantic Time-Series Studies (BATS; Karl, 1992; Knap, 1992; Michaels, 1992). The U.S. time-series scientific programs benefits from the proximity of laboratory facilities on the Hawaii and Bermuda islands. However, the circumstances providing laboratories close enough to oceanic sites with offshore characteristics of interest for JGOFS objectives are relatively rare. In addition, though these stations are both located in two different oceans and biogeochemical provinces, they both characterize low latitude environmental conditions.

The program KERFIX proposes a time-series station at a fixed location 60 nautical miles southwest of the Kerguelen Islands (KERFIX: 50°40 S, 68°25 E, Figure 1). It started in 1990 and was the first regular multiyear acquisition of parameters in the remote Southern Ocean, known for its particularly cold and windy environment. Since 1991, another long-term research was developed in the Southern Ocean, but near the Antarctic continent, in the framework of the PALMER LTER program (Smith *et al.*, 1995). This last program is mostly focused on the spatial and temporal variability of the primary production in this area and their link with the annual advance and retreat of sea ice.

Apart from quantifying the temporal variations of the carbon flux, the program KERFIX proposes several more specific studies. One of the main motivation of KERFIX is to contribute to the understanding of the processes that control the primary production, which paradoxically is very weak in this nutrient-rich region. The majority of the parameters acquired as part of KERFIX will be discussed on the basis of simulations using a one-dimensional physical/biological/chemical coupled model (GEOTOP, extensively described in Ruiz-Pino *et al.*, 1995). This model has been developed simultaneously with the settling of KERFIX and was of a great help for establishing the sampling strategy. The physical characteristic of the area have been studied to define the seasonal and interannual variability of the thermal content and the steric height of the water column. Current meter data will allow the determination of the average current and its variability with time. Temporal series of dissolved and particulate lithogenic and biogenic Si and Ba data will help to improve our knowledge of their geochemical cycles and more particularly by which mechanisms they are (or not) coupled (Dehairs and Goeyens, 1989; Dehairs *et al.*, 1995; Jeandel *et al.*, in press; Stroobants *et al.*, 1991). Finally, a micropaleontological study aims to quantify the influence of the seasonal cycle on the $^{13}C/^{12}C$ content of

Fig 1

Figure 1
Locations of the Kerfix and Bio-stations. The map also shows the bathymetry isolines.



foraminiferas and the productive components of diatoms. This last point should improve the knowledge of the transfer function of these proxies of paleo-production and their paleo-oceanographic applications.

The KERFIX program, initiated in 1990 by A. Poisson (LPCM, Paris), is guided by C. Jeandel since 1993 and was completed in March 1995. We will present hereafter some preliminary results. They give an idea of the data base structure, currently being worked out.

I- Program organization

I-1 Sampling sites

The Southern Ocean, defined as the ocean within the Sub-Tropical Convergence (e.g., South of the Subtropical Front) accounts for more than 20% of the area of the World Ocean. It is characterized by very low surface temperatures and an area of deep water formation. Thus, the study of its role in the air-sea exchange of CO_2 is of a first importance. However, because of the rough meteorological conditions affecting this remote area -- mostly in winter! --, undertaking ship-based studies over the entire year is a (difficult) challenge. Laboratory facilities have been developed on the Kerguelen Islands since the beginning of the fifties. More recently (1989), the "Institut Français pour la Recherche et la Technologie Polaire (IFRTP)" has acquired a coastal oceanographic ship of 25 m length, "La Curieuse" that is based on Kerguelen Island. This motivated the implementation of a scientific program consisting in a continuous survey of physical, biological and chemical parameters on a selected location, characteristic of the southern part of the Polar Front Zone (PFZ) in the Southern Ocean: KERFIX. The exact location of the sampling station has been selected to satisfy the following constraints: being a-weather the island, presenting enough depth for coming across offshore conditions and a relatively flat bathymetry for a mooring equipped line with sediment traps. On the other hand, the site had to be close enough from the island for reducing the transit time to a maximum of 12 hours, for a boat like "La Curieuse". Thus, the station was settled at 50°40 S, 68°25 E, 60 miles southwest of the Kerguelen Islands (Figure 1).

During 1993, the regular visit of a second site, located only 15 miles off KERGUELEN, the Bio-Station (Bio St, Figure 1), has been decided to recover active zooplankton to perform grazing and respiration studies. The consistency between the KERFIX and Bio St zoo planktonic populations was checked regularly by S. Razouls (unpublished data).

I-2 Sampling

For any given permanent station, the number of parameters and the sampling periods selected depend on the location of the station, the capacity of the investigating team and the size of the sampling ship. The number of measurements made at KERFIX site has progressed in time, a direct consequence of the improvement in the number and quality of equipments. The parameters acquired as parts of KERFIX are compiled in Table 1, together with their acquisition period and the name of the laboratory in charge of each parameter. Few "fine process" studies were developed as part of KERFIX, compared to research projects proposed in the framework of other time-series (e.g., *In situ* primary production measurements, or dimethyl sulfide production, consumption and exchange or trace element cycling etc....; Malone *et al.*, 1993; Michaels, 1992; Roman *et al.*, 1993). This is due to the very long distance of Kerguelen Islands from France (which is reached from La Reunion island after a 7 day cruise of R/V "Marion-Dufresne"), and the to rough meteorological conditions hampering sampling and measurements.
"La Curieuse" visited the KERFIX site on an approximate monthly rate for hydrological (P, T, S, O_2, CO_2, alkalinity and nutrients), biological (phyto-, zoo- and bacterio-plankton), and geochemical sampling (filtered suspended particles). Water samples were collected using 8l Niskin bottles mounted on a stainless steel cable and equipped with reversing SIS pressure and temperature instruments. Hydrological and bacteriological samples were collected at 24 depths between 0 and 1500 m. Total Suspended Matter (TSM) typical sampling depths were surface; 10; 40; 75; 150; 350 and 500m. Back at the shore-based laboratory, samples were transferred to perspex filtration units and filtered on Nuclepore membranes (0.4 micrometer porosity) under filtered air pressure. Filters were dried at 50°C and stored in petri dishes for later analysis (Dehairs et al., 1995). Chla was sampled on the surface cast only. Zooplankton was sampled by vertical hauls (300 - 0 m) using a Bongo net (200 µm mesh - sized). The alternate visits made to the Bio Station were devoted to the catch of live zooplankton and sampling of natural sea water for biological experiments (Razouls *et al.*, 1995; Razouls *et al.*, this issue).

From April 1993 to March 1995, a mooring has been deployed at the same site. This allowed the continuous measurements of the downward flux of particulate material using Technicap sediment trap (PPS5, 1m^2 section, 24 cups, moored at 200 and 1000m) and currents from the associated current-meters (Aanderaa RCM7). The time resolution of the particle collection is of one month in winter and 7 to 10 days during the more productive months of spring and summer.

Recovery cruises to maintain the moorings occured annually, with R/V "Marion-Dufresne". This boat is large and well equipped with laboratories and a rosette mounted on a Continuous Temperature Depth profiler (CTD) for hydrological sampling. A first mooring line was deployed in April 1993, recovered and re-deployed in February 1994. A second mooring line was recovered in March 1995.

I-2 Analysis

As the KERFIX participants will publish their analytical procedures elsewhere, we only recall here the main lines of these protocols.

Kerguelen

An important part of the measurements was made by two "Volontaires à l'Aide Technique" - technical assistants carrying their military service - at Kerguelen, using the "BIOlogie MARine" (BIOMAR) laboratory facilities. These measurements are identified as "Kerguelen" in Table 1. Temperature and pressure were acquired on-board by SIS sensors. Salinity was determined using an Autosal Guideline salinometer. Dissolved Inorganic Carbon and alkalinity were measured using a Dickson titration (protocol adapted from Edmond (1970) and Bradshaw *et al.*, (1981) by C. Brunet and his collaborators at LPCM laboratory, as detailed in Poisson *et al.*,, 1987). Dissolved oxygen was measured by a Winkler titration (following Carpenter, 1965). Silica, phosphate and ammonium were determined manually, on a Kontron spectrophotometer. As most of the problems affecting the data acquisition were due to the rough sampling conditions, we will explain in the next section how the data were validated.

Kerguelen/ Metropolitan

Other samples were pretreated in Kerguelen, and then analyzed in France, Monaco or Belgium.

Chlorophyll-a (chl*a*) and phaeopigments were extracted with 90% acetone and their concentrations measured using a spectrofluorometer (Perkin Elmer MPF 66; Neveux and Panouse, 1987).

Concerning the zooplankton, one tow was preserved (5% formaldehyde) for identification and animal counting. Another one was used for dry biomass (Lovegrove, 1961) and further carbon and nitrogen analysis with a Perkin Elmer Analyser 2400. Live plankton was brought to the laboratory and copepods were picked up within a few hours after capture. Biological process experiments were performed under *in situ* conditions (natural sea water collected

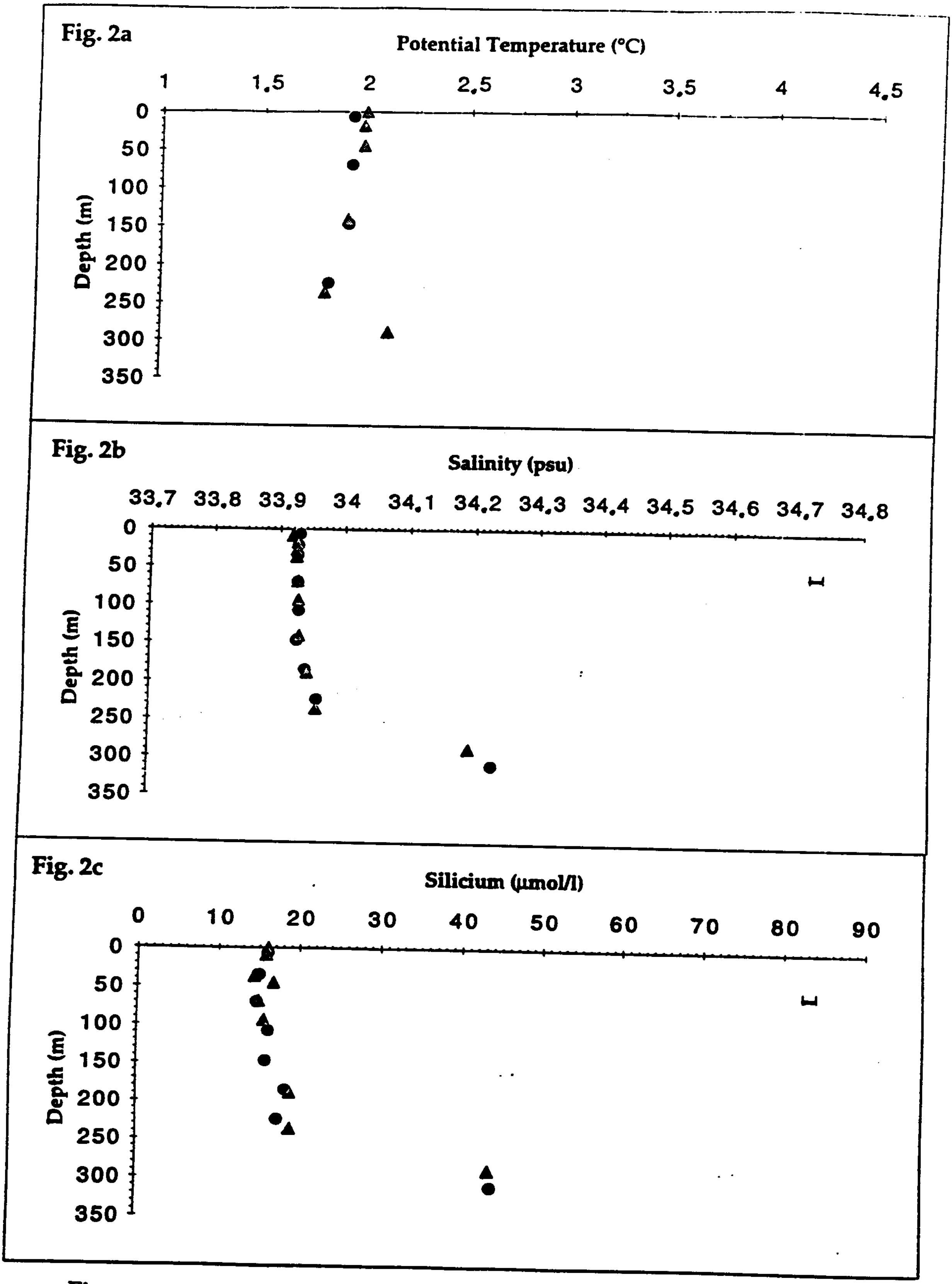


Figure 2
Results of potential temperature (2a), salinity (2b) and silica (2c) analysis performed on duplicates of the surface cast. The black circles correspond to the first cast and the gray triangles to the second one, 6 hours later. Error bars are indicated on the upper right of the figure.

simultaneously with zooplankton and maintained at constant temperature). Grazing rates were estimated by the incubation method (Frost, 1972) and the chl*a* was analyzed using a Turner Design fluorometer (Strickland and Parsons, 1968). The chl*a* results obtained with the Turner (at Kerguelen) and the Perkin Elmer (at Banyuls) apparatus are consistent. Oxygen consumption rates were measured using the Clark type electrode (Strathkelvin oxymeter, Razouls *et al.*, 1995; Razouls *et al.*, submitted) Total bacteria were determined by acridine orange direct count (AODC) following the method of Hobbie et al. (1977). Particle related and free living bacteria were counted separately. Biovolumes were estimated using an ocular micrometer. Frequency of dividing cells (FDC) was assessed using the method of Hagström et al. (1979).

The incubations ($^{15}NO_3$, $^{15}NH_4$, ^{30}Si) were made *in situ* and the samples were filtered, stored and analyzed later.

Metropolitan

Other samples were simply stored for further analysis. This is the case for nitrates, for which samples were frozen and analyzed at the Université de Bretagne Occidentale using a Technicon Auto-Analyzer II. This concerned also the dissolved $\delta^{13}C$ on Dissolved Inorganic Carbon (DIC) and the trapped and filtered samples (Table 1).

The mass and carbon fluxes of the sediment trap samples were determined on a desalted and freeze-dried aliquot after removal of swimmers and sub-sampling. Total carbon and nitrogen were measured using a CHN analyzer (HERAEUS); inorganic carbon was measured using a UIC coulometer and the total organic carbon computed from the diffrence between total and inorganic carbon. Zooplankton fecal pellets were enumerated in a liquid sub-sample and categorized according to their geometric shapes (Miquel *et al.*, 1995).

For the total analysis of Ba, Sr, Ca and Al, the trapped sample aliquot (or the Nuclepore membrane for TSM) was digested in Teflon bombs using Suprapur grade HNO_3/HCl. After digestion, volumes were made up to 10 ml (for TSM filters) or 50 ml (for sediment trap samples). Element concentrations were determined using a Jobin-Yvon JY-48 simultaneous (Ca, Sr, Al) and JY-38 sequential (Ba) ICP Optical Emission Spectrometer (Dehairs et al., 1995).

The analysis of $\delta^{13}C$ on trapped material was performed on about 3 mg of dried material. A few drops of 1 N HCl were added while the sample cup was heated to 80°C, to eliminate carbonates. This was repeated till no more effervescence was detected visually. Samples were combusted in a Carlo Erba NA 1500 CN analyzer and CO_2 gas was cryogenically trapped in an automatic trapping-box, on-line between CN-analyzer and mass spectrometer. Then,

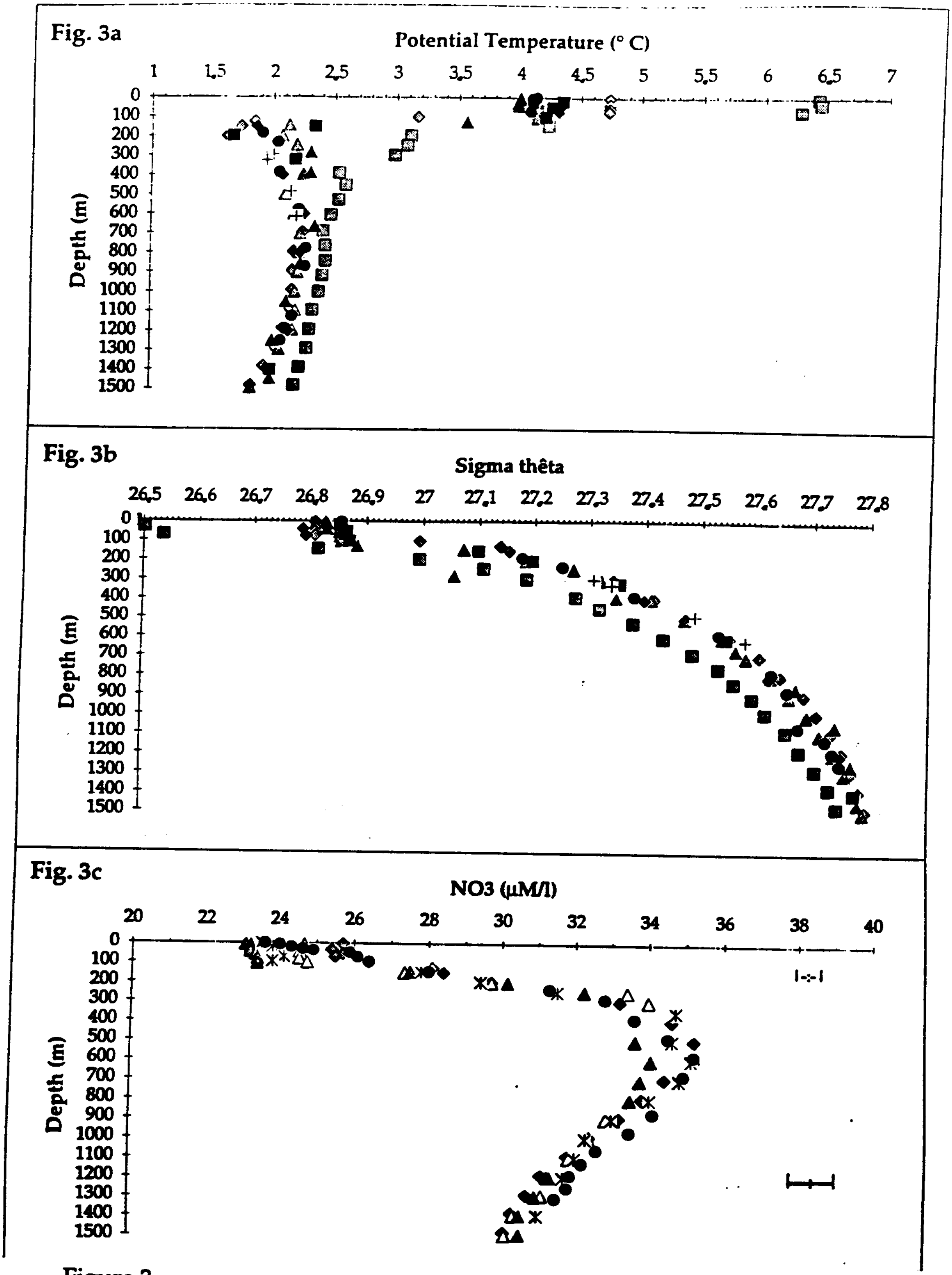


Figure 3
Comparison between data obtained at KERFIX station with "La Curieuse" (March 90, 91, 92, 93 and 94: black squares, lozanges, triangles and circles respectively) and other data obtained using a rosette on a CTD on large oceanographic vessels: GEOSECS data are from St 429, August 1978 (gray squares), INDIGO data are from St 16, March 85 (gray triangles); CIVA and ANTARES have been acquired simultaneously with the "Marion-Dufresne" and "La Curieuse" at the KERFIX station in January 1993, March 1993 and February 1994 (white triangles, gray triangles and black stars, respectively). Our data errors are indicated on the right of each curve (see text).

conditioned CO_2 gas was injected into the mass spectrometer (Finnigan-Mat Delta-E). A reference material (USG 24, graphite) was run at the beginning and end of each series of daily analyses. $\delta^{13}C$ results are expressed relative to the PDB standard. For $\delta^{15}N$ analysis, about 15 mg of dried sediment trap material were weighed in a tin cup and combusted in the Carlo Erba NA 1500 CN analyzer. N_2 gas were trapped cryogenically subsequently to cryogenic trapping of water vapor and CO_2. N_2 traps were fitted manually to the mass spectrometer. IAEA N-1 and N-2 reference materials (ammonium sulphate) were run during each series of samples. Results are expressed relative to the composition of atmospheric N_2 (Dehairs *et al.*, 1995).

For electron microscopy, a small piece of Nuclepore filter was cut out and prepared for SEM-EMP analysis. Samples were analyzed half-automatically at 200X magnification. Particle selection was achieved based on their brightness and Ba plus sulfur occurence. Particles recognized as barites were sized. The obtained projected particle surface was considered similar to the projected surface of a sphere. A particle volume and Ba mass were calculated taking a value of 4.5 for barite density. Final results are expressed in pmol Ba (as barite) per liter (Dehairs et al., 1995).

II- Results

II-1 Data Precision and Validity

Precision

The KERFIX samples were collected using bottles on a cable, taken from a small boat that is very unstable (to say the least) in the conditions of the famous "Yelling Fifties" The logistical constraints implied a long and tricky process for the data acquisition. Therefore, raw data acquired on Kerguelen Island required a great deal of processing and validation before publication. This work was initiated by Diana Ruiz Pino and her team (LPCM) and is still underway.

The precision of the parameter acquisitions was controlled regularly by the measurement of triplicates, i.e. the anälyzis of three aliquots of the same sampling bottle. For each parameter, monthly average values for the mixed layer were also established. The standard deviation of this average (obtained on 8 to 12 data) allowed another estimation of the measurement precision, assuming that concentrations are homogeneous in the mixed layer. In addition, several surface casts have been duplicated, in order to i) check that the water sampled remained stable during the time of sampling (6 hours) and ii) provide an internal

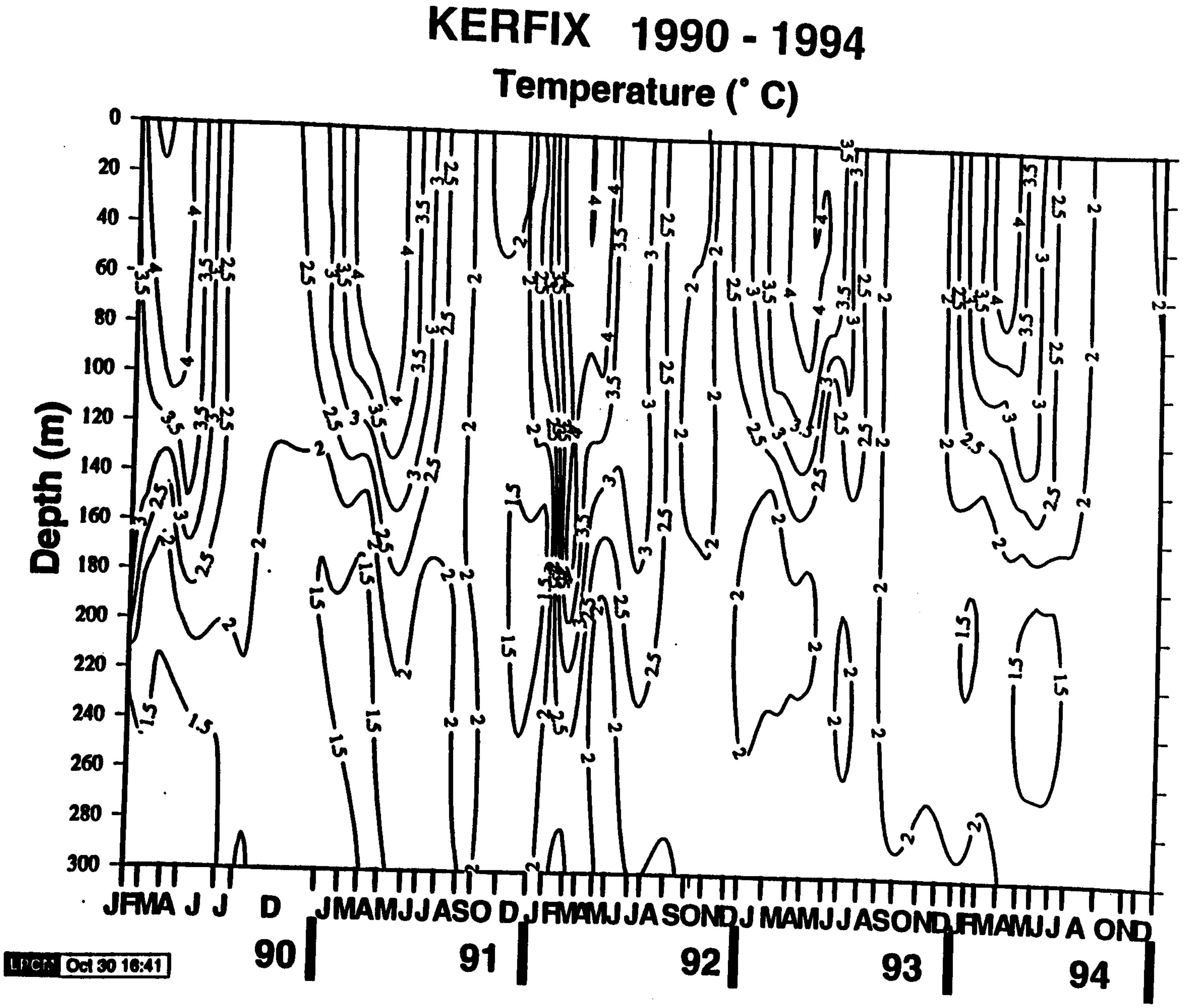


Figure 4
Temporal section of temperature measured in the first 300 m between 1990 and 1994.

comparison of our results. As an example, duplicate data obtained in November 1993 gave satisfying results (Figure 2). The final precision of our data takes into account these three approaches. We estimate that the resulting uncertainties on the potential temperature, salinity, oxygen, alkalinity, total inorganic carbon, silica, nitrate and phosphate are ±0.005°C, ±0.006, ± 3 μmol/kg, ±0.003 meq/kg, ± 2%, ± 1% and ± 1 to 3 %, respectively. The larger uncertainty on phosphate data results from the manual technic and the success of this measurement is closely dependent on the analyst's skills, while they were a different every year.

Validity

In order to assess our data, we compared them to i) historical data acquired in the same area with the "Marion-Dufresne" in the framework of preceding programs (ANTIPROD (Fr) and INDIGO (Fr)) and ii) simultaneous data acquired with "La Curieuse" and the "Marion-Dufresne" when concomitant sampling was possible (e.g., in January and March 1993 during the CIVA 1 cruise (WOCE) and in February and March 1994 during the ANTARES 2 cruise (F-JGOFS). We also compare our data to the historical GEOSECS 429 station (47°46 S, 58° 02 E), though this station is located at about 280 nautical miles north-west of KERFIX station. Examples of these comparisons are given in Figure 3. They show that the processed KERFIX data are similar to those obtained with the "Marion-Dufresne" with calibrated CTD and, for the nutrients, with data acquired on Technicon Auto analyzer II following the WOCE and JGOFS recommendations (Gordon *et al.*, 1994). They are also close to the GEOSECS results, though the two sites do not exactly sample the same water-masses.

II-2 First Results

The KERFIX sampling program ended in March 1995; so we cannot yet discuss in details all the results presented here. This will be done in forth-coming papers, under the responsibility of each participant. Instead, we propose a survey of our result's potentials.

Physics

Figure 4 shows the temporal evolution of temperature in the upper 300-m water column from 1990 to 1995. In these waters, a seasonal well-marked cycle can be observed, in spite of a yearly background of low temperatures. The higher temperatures range between 3.7 and 4.3 °C in February and March. The coldest surface waters (1.6 to 2 °C) are observed in August. The annual range of surface temperature variations is about 2.5°C and shows the evolution from a stratified

Fig. 5

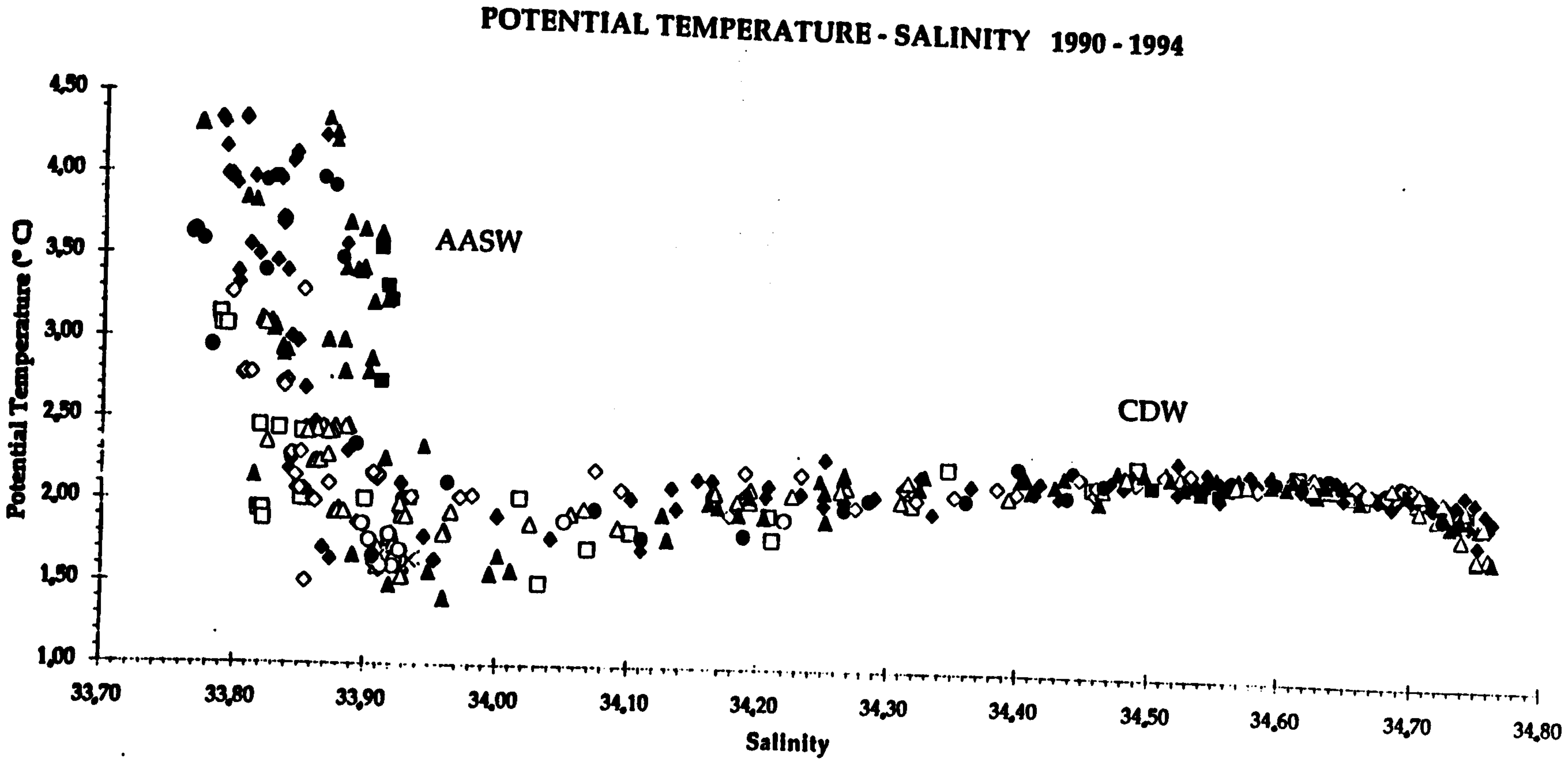


Figure 5
Potential temperature versus salinity diagram characteristic of KERFIX station, established from 4 years of data. The white symbols correspond to the "winter" months (June to November) and the black symbols represent the "summer" months (October to May). AASW: Antarctic Surface Waters and CDW: Circumpolar Deep Waters.

system with a deep thermocline in summer, towards a winter situation with a deep homogeneous water column (Park *et al.*, this issue). Two water masses are identified on the potential temperature (Θ) versus salinity diagrams (Figure 5): the Antarctic Surface Waters (relatively fresh and characterized by a temperature minimum) and the Circumpolar Deep Waters (more salty, $\Theta > 0°C$). A significant interannual variability of the heat content and steric height of the water column is observed, the year 1992 being the warmest and 1994 being the coldest. In this issue, Park *et al.* paper discuss the origin of these variations. The first statistical analysis of the current meter data recorded during 8 months (deployed at 200 m and 1000 m on the mooring line between April 1993 and February 1994) shows surprisingly westward currents at both depths at the KERFIX site. These counter-currents seem to be related to a recirculation pattern South of the Kerguelen Plateau (Park *et al.*, 1995).

Biogeochemistry

The temporal section of the silica results (measured between 1992 and 1994) indicates that concentrations are never completely depleted at the surface (Figure 6), even though seasonal variations are observed. At the surface, silica concentrations vary between 3 to 8 µmol/kg (in summer) and about 20 µmol/kg (in winter) and increase until 80 µmol/kg at depth. For phosphate and nitrate as well (not shown) surface values are always above zero in this area, confirming that nutrients are not limiting primary production.

The main feature marking the sub-Antarctic waters is the general oligotrophy in terms of phytoplankton biomass. However, the chl*a* content shows seasonal changes. During winter and spring, the chl*a* concentration in the euphotic zone is always below 0.2 mg. m^{-3}. It increased dramatically from September to December to reach a maximum value of 1.2 mg. m^{-3} in November-December between the surface and 60 m depth (Figure 7, Fiala *et al.*, 1995). In any case, the "KERFIX" site is located in a "HNLC" area (High Nutrient Low Chlorophyll) where the "production paradox" is particularly intriguing: why primary production is so weak when there is an abundance of nutrients?

Copepods (size 0.5 to 8 mm) are the main constituents (> 90 %) of the meso- and macro-zooplankton catches. Their numbers can vary from less than 10. m^{-3} in winter, to 700. m^{-3} in summer and the average biomass reflects these seasonal changes. Ingestion rates of copepods, estimated *in situ*, remain at low levels, between the extreme values of 0.003 and 69 ng Chl*a* . h^{-1} . mg $^{-1}$ with grazing rates varying between 0. 011 and 160 ml of filtered water . h^{-1}. mg^{-1} (mg of Dry Weight: D.W.). The respiration rates confirm a low metabolism. These data suggest a poor utilization of the phytoplanktonic chlorophyll in the KERFIX area

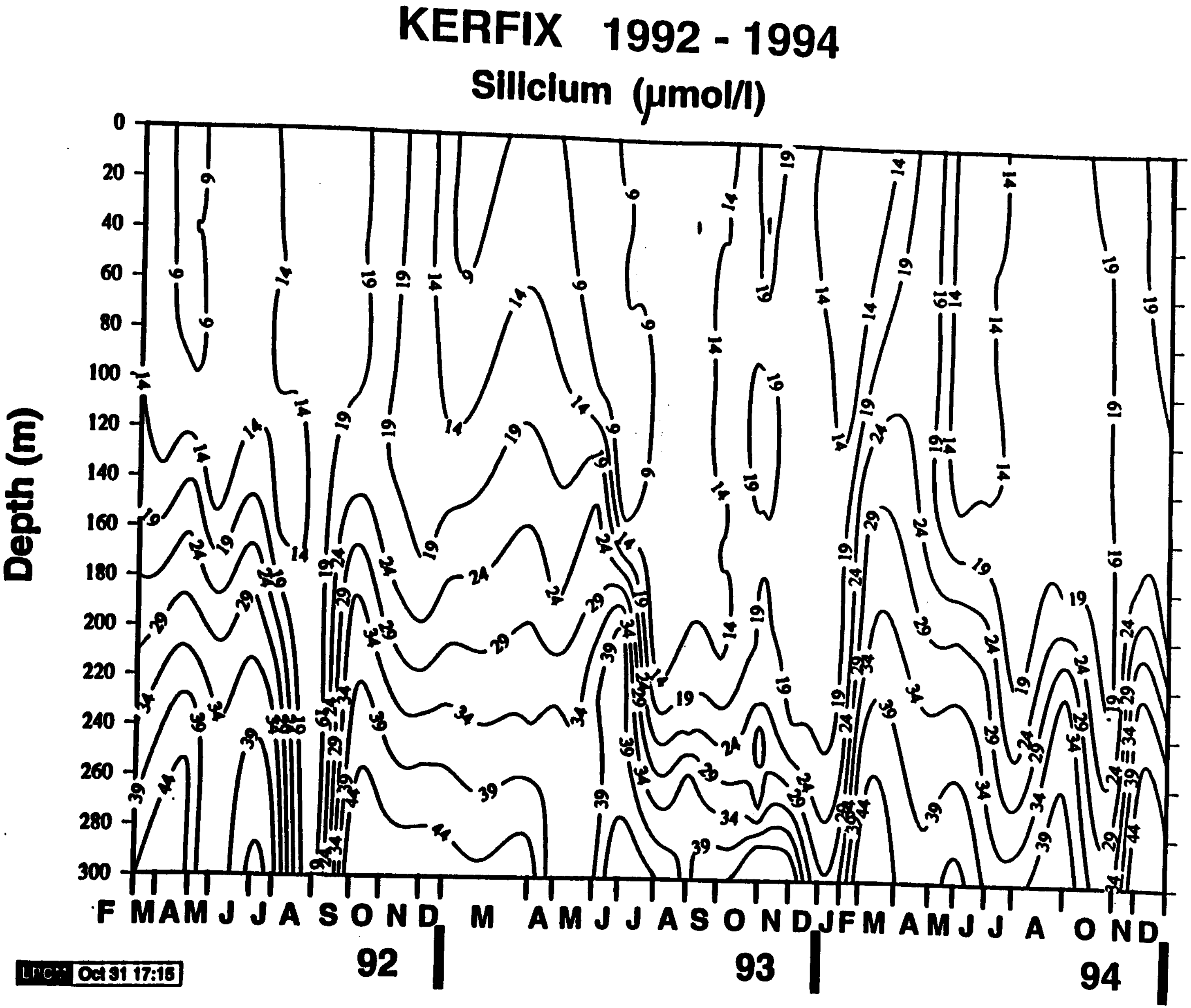


Figure 6
Temporal section of silica data measured at KERFIX between 1992 and 1994.

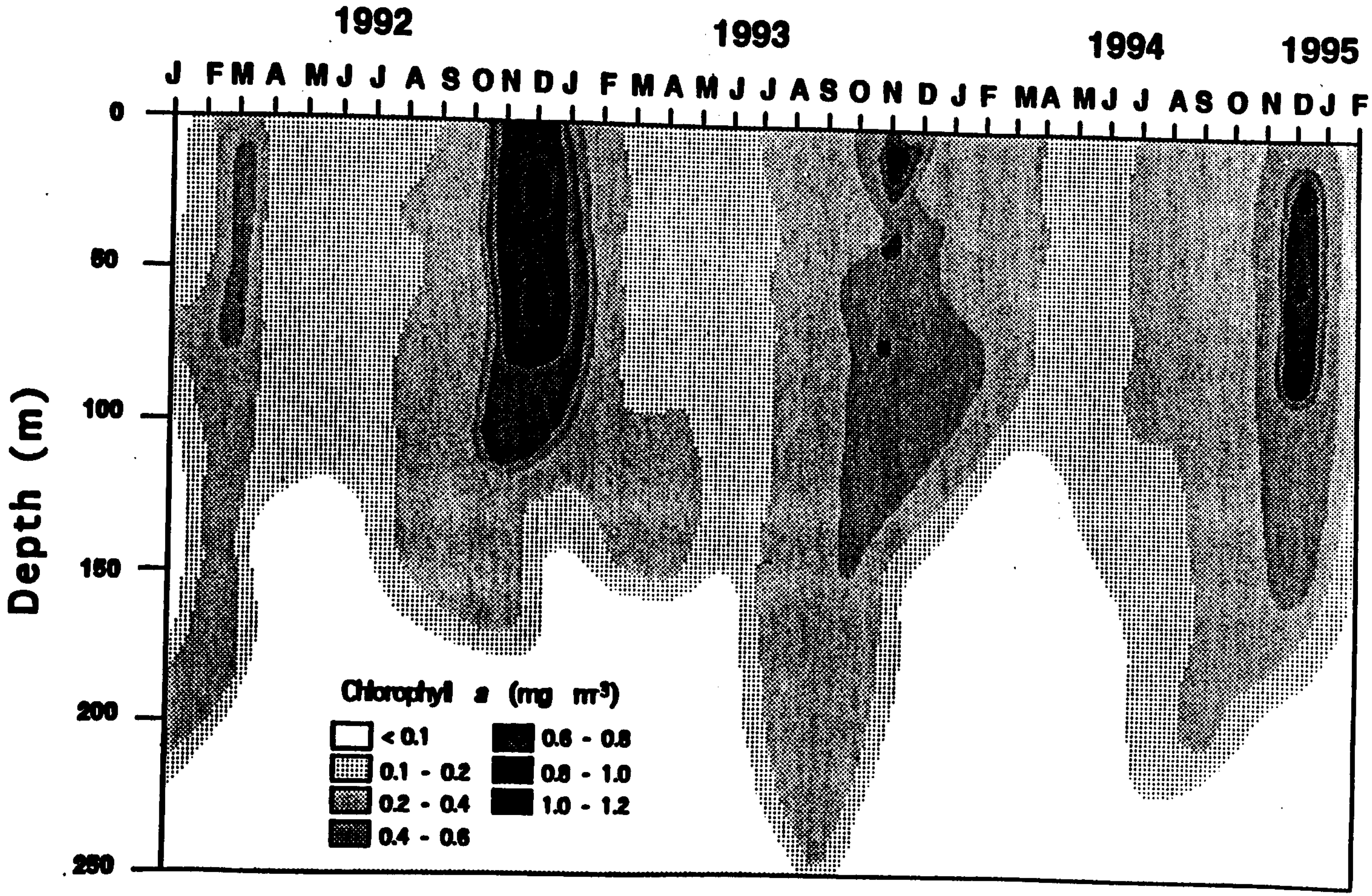


Figure 7
Temporal section of the chlorophyll-a measured at KERFIX between 1992 and 1994.

Fig. 8

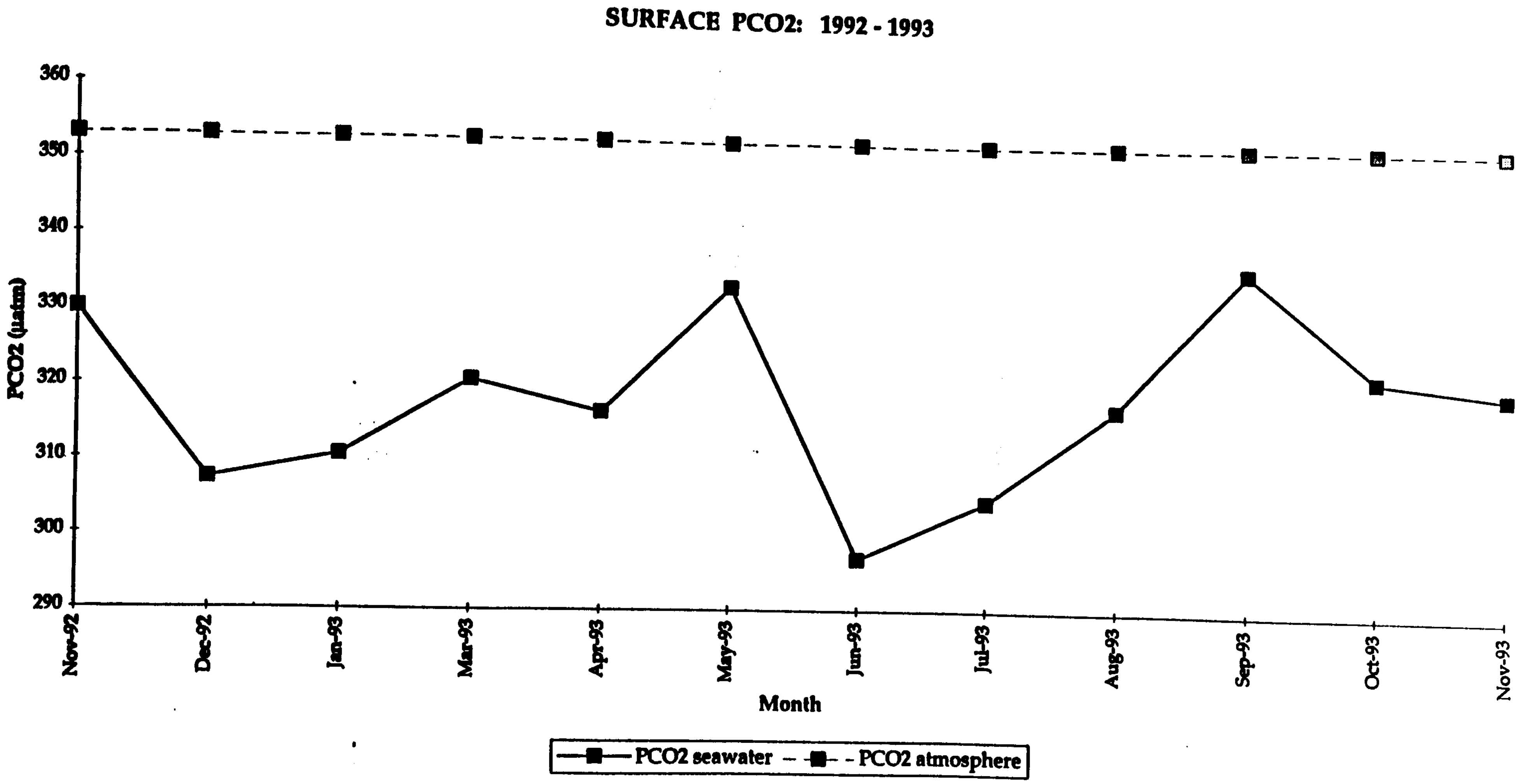


Figure 8
Surface water pCO_2 calculated for each month of 1993 at the KERFIX station.
The atmospheric data have been measured in the framework of MINERVE program (see the text).

(Razouls *et al.*, 1995; Razouls *et al.*, this issue). In addition, recent results of De Baar *et al.* (1995) and Sarthou *et al.*, (1995) show that iron is likely not limiting in this Frontal area. Other parameters should limit the primary production such as mixing, micro-zooplankton grazing, temperature or light. The set of data collected in the framework of KERFIX will allow to test the importance of these factors using the GEOTOP model.

Total bacterial abundance ranges between $5x10^4$ and $8x10^5$ cells ml^{-1} with an annual mean value of $3x10^5$ cells ml^{-1}. There is a clear, decreasing, gradient from the surface layer to the deepest studied layer (1500m). Maximal abundances are generally recorded in sub surface layers (between 20 and 150 m). The largest bacterial communities occurs in December, the lowest in October. Mean cell volumes range between 0.05 and 3.0 μm^3 with an annual mean value of 0.1 μm^3. In contrast to total bacterial abundance, there is no clear vertical gradient in the distribution of mean cell volumes. However, some dramatic increases are sometime recorded in relatively deep layers (0.3 μm^3 at 500 m in March 1993). The bacterial biomass ranges among 2 and 15 $\mu gC. l^{-1}$ and decreases regularly from sub surface layers to the deepest layer. The frequency of dividing cells (FDC) is always low (among 1 and 4 %). The proportion of free living bacteria is always large (close to 80% of the total bacterial abundance; Delille *et al.*, 1995).

pCO_2

The pCO_2 values are calculated ofrom TCO_2 and alkalinity data. The resulting values are in good agreement with the ones measured at the same time, during the MINERVE program at the KERFIX area (MINERVE proposes a continuous acquisition of the pCO_2 content of the surface waters during the transects of the "Marion-Dufresne" and is driven by A. Poisson; Metzl *et al.*, 1995). Figure 8 shows the average pCO_2 values obtained in the mixed layer, for the year 1993, in comparison with the atmospheric pCO_2, also measured during the MINERVE operation (Metzl et al., 1995). These data (12 measurements along the year, which is the half of the number recommended by Garçon et al., 1992) show that the mixed layer pCO_2 is always below the atmospheric one, the deficit varying between 20 and 50 µatm. This suggests that this area acts as a permanent sink for the atmospheric CO_2, at least for the year 1993. However, the relative importance of the processes yielding the surface pCO_2 have to be closely studied, including the solubility and biological pumps, as well as vertical mixing. This will be done using the GEOTOP model.

Exported fluxes and suspended particles

Fig. 9a

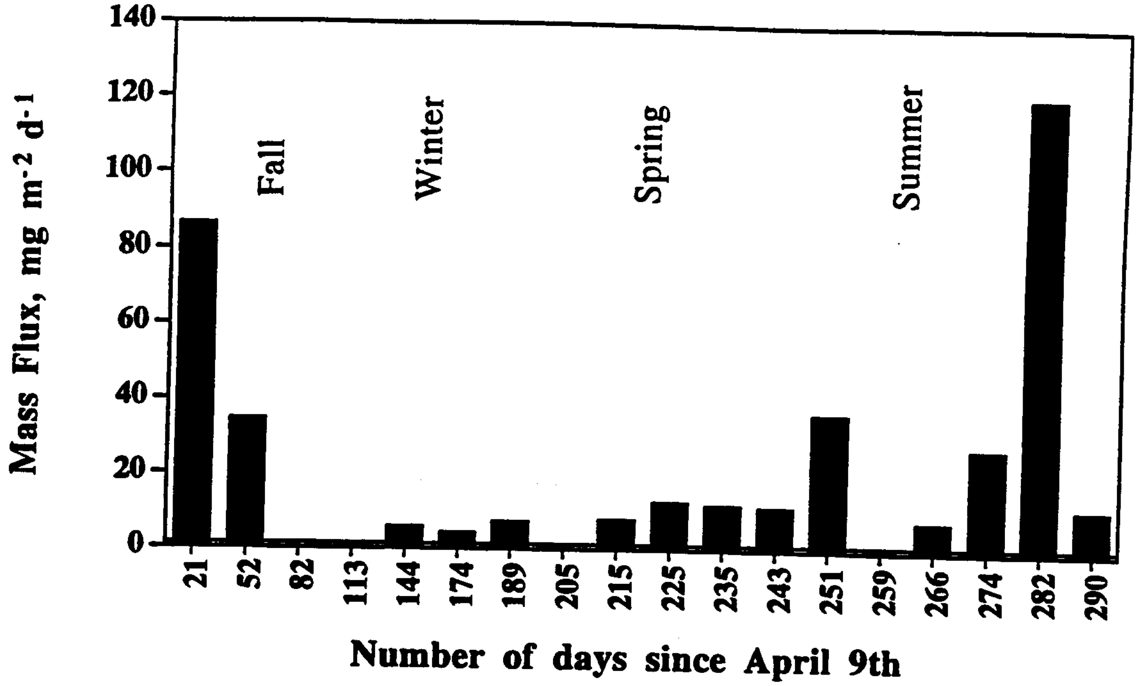


Fig. 9b

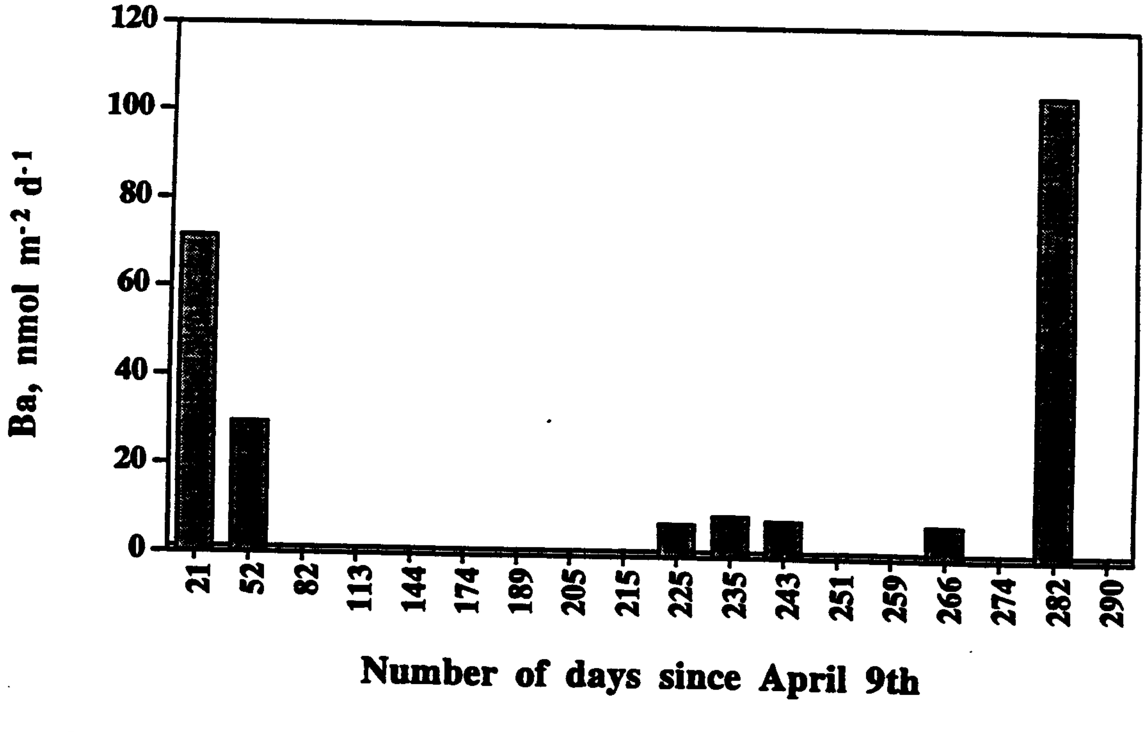


Figure 9
Mass flux (mg.m^{-2}.d^{-1}; 9a) and Ba flux (nM. m^{-2}.d^{-1}; 9b) temporal series over the year 1993/1994 measured in the 200-m KERFIX sediment trap.

From trapped samples, the mass flux and organic carbon, inorganic carbon, nitrogen as well as Al, Ca, Sr, and Ba fluxes have been measured between November 1993 and February 1994. The mass flux and the fluxes of Al, Ca and Ba show similar variations. Thus, we represented only Ba and total mass flux in Figure 9. The mass flux has maximal values both in Fall and Summer (january) and minimal values in winter and spring. Our summer flux is 12 times lower than the maximum flux measured in the Bransfield Strait, whereas the winter minimas are comparable in both studies (Wefer *et al.*, 1988). These differences have to be related to the contrasting biomasses characterizing these two areas: both are in the Southern Ocean, where the "bloom" is centered on the summer months but the Antarctic Peninsula is known for its large biomass (chl*a*>20 mg/m^3, Karl *et al.*,, 1991), that is 20 times greater than our chl*a* measurements (see above).

The first data on Ba in the trapped samples indicate that concentrations remain relatively constant with time. The seasonal variations are essentially accounted for by the variations of the mass flux.

The first results on Total Suspended Matter (TSM) samples were obtained in the mesopelagic layer (300, 500 m) between December 1993 and November 1994. They show a barite micro-crystal maximum in January 94 and then regularly decreasing values till October. In November, the concentrations increase again, but stay under the values observed in January (Dehairs *et al.*, 1995).

Comparison between the suspended Ba fraction (carried by barite crystals) and the trapped Ba flux shows significantly less seasonal variations in the suspended matter than in the trapped one. All the flux variations will be investigated more closely on the base of particle composition and morphology.

CONCLUSION

For 5 years, the program KERFIX proposed a long-term survey of hydrological, biological, chemical and physical parameters off the KERGUELEN island. Eventhough collecting the samples is difficult in this area, the KERFIX data have good precisions, allowing to draw preliminary conclusions. Two water masses are identified at KERFIX, namely the Antarctic Surface Waters (AASW) and the Circumpolar Deep Waters (CDW). The upper water column is stratified in summer and well mixed in winter. The thermal and density properties of the Oceanic Mixed Layer (OML) show seasonal and interannual variations, the warmest year being 1992 and the coldest 1994. Westwards counter-currents are evidenced for the first time in this area. The grazing pressure of the copepods (which largely dominate the zooplanktonic biomass) on phytoplankton is not significant. Iron do not seem to be limiting in this area. Thus, the process limiting production is not identified yet. The KERFIX program, thanks to its long time series with many parameters, proposes a set of data which allows to contribute to explain the paradox of the Austral Ocean, rich in nutrients but characterized by a low primary production. On the basis of 12 measurements along the year 1993, the data show that KERFIX area could act as a sink for atmospheric CO_2, but a more precise study of the parameters controlling the gas exchange is still to be made. The relative importance of the processes at play will be tested using the GEOTOP 1D physics/chemistry/biology coupled model, written in the framework of KERFIX. The vertical flux of matter is low. A close study of the seasonal variation of the phytoplankton taxonomy and a comparison between the suspended material and the trapped one will help to identify the main biological component of the fluxes. The study of the seasonal and interannual cycles of some elements (Si, Ba, $\delta^{13}C$...) will also help to progress in the knowledge of their oceanic biogeochemical cycles and to refine their paleo-applications.

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