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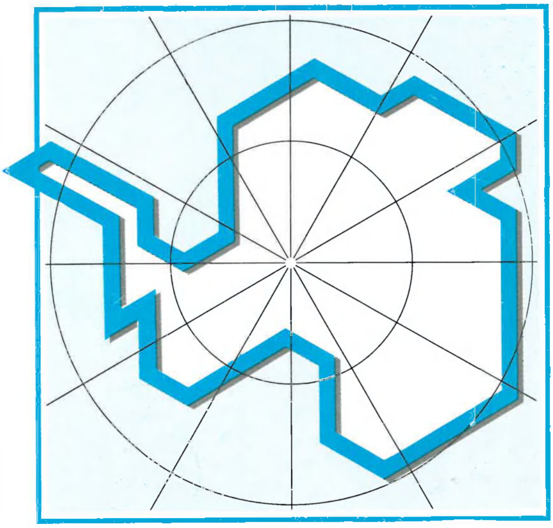

PROCEEDINGS OF THE BELGIAN NATIONAL **COLLOQUIUM ON ANTARCTIC RESEARCH**

(BRUSSELS, OCTOBER 20, 1987)

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Prime Minister's Services
SCIENCE POLICY OFFICE
Wetenschapsstraat - 8 - rue de la Science
1040 Brussels
D/1988/1191/11

The Colloquium was organized by the Science Policy Office – Prime Minister's Services, Brussels

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PREFACE

This volume contains oral papers presented at the "Belgian National Colloquium on Antarctic Research" held in Brussels (Belgium) on October 20, 1987.

The Colloquium was organized within the framework of the "Belgian Scientific Research Programme on Antarctica" (1985–1989) directed and managed by the Science Policy Office – Prime Minister's Services. The programme was implemented through the decision of the Council of Ministers of July 29, 1985 with the aim at contributing to the international effort to develop scientific knowledge on the Antarctic.

It was aimed at giving an overview of the current progress achieved in Belgium in that field in relationship with research activities carried out in countries which hosted Belgian scientists involved in the programme.

Brussels, March 1988

A. STENMANS
Secretary General of the Science Policy Office,
Chairman of the Colloquium

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OPENING ADDRESS

Louis BRIL
Secretary of State for Science Policy

Dames en Heren,

Het is mij een genoegen bij de aanvang van deze studiedag van het Wetenschappelijk onderzoekprogramma betreffende het Zuidpoolgebied tot U het woord te kunnen richten.

België heeft zich inderdaad steeds nauw betrokken gevoeld bij dit fascinerende deel van de wereld en ons land was één van de voorlopers inzake de wetenschappelijke exploratie van Antarctica.

Het statuut van Consultatieve Partij waarvan België sinds de ondertekening van het Antarctisch Verdrag in 1961 geniet, bevestigt deze betrokkenheid.

Het hoeft geen betoog dat er op universeel vlak een vernieuwde interesse heerst voor dit nog ongerepte continent. Deze vernieuwde interesse kadert enerzijds in het vooruitzicht van de mogelijke herziening van het Antarctisch Verdrag in 1991 en anderzijds rijst het besef dat dit nog niet door de mens verstoorde continent als het ware een immens laboratorium is waar bepaalde verschijnselen kunnen worden bestudeerd die mogelijks gevolgen hebben op wereldschaal.

België is er zich bewust van dat dit continent en de omringende zeeën een zeer interessant studiegebied zijn en dat dit beschermd dient te worden tegen mogelijke menselijke invloeden die het milieu zouden schaden.
Het is in deze context dat de Ministerraad in 1985 besliste een "Wetenschappelijk onderzoekprogramma betreffende het Zuidpoolgebied" op te zetten, om ervan te getuigen dat ons land wil bijdragen aan het internationale onderzoek ter verruiming van de wetenschappelijke kennis omtrent het Zuidpoolgebied.

Ce programme est conçu comme une action thématique pluriannuelle regroupant des études spécifiques exécutées par six universités du pays et une unité scientifique de service public sous la coordination des Services de Programmation de la Politique scientifique.

Le programme a été élaboré de manière à intégrer l'action de la Belgique dans les priorités de politique scientifique nationale et internationale dans le respect des moyens budgétaires de notre pays.

Il comporte un triple objectif :

a) Renforcer en Belgique un noyau de compétence et d'expertise permettant à notre pays d'être présent dans les activités scientifiques mises en oeuvre au niveau mondial pour l'étude de l'Antarctique, conformément à l'esprit du Traité sur l'Antarctique.

b) Axer l'essentiel de l'effort de recherche autour de deux domaines principaux qui, conformément à un large consensus international, réclament un effort de développement prioritaire en raison de l'étendue de leurs implications pratiques et compte tenu de l'état des connaissances. Ces deux domaines sont l'écologie du plancton qui conditionne toute la chaîne alimentaire marine, et la glaciologie en relation avec ses implications climatologiques, soit précisément deux domaines où existe un potentiel scientifique belge de valeur.

c) Apporter une "valeur ajoutée" scientifique aux recherches en cours dans un certain nombre d'équipes universitaires d'excellence (actives notamment dans des programmes internationaux de R&D) en veillant, par une gestion et une coordination appropriées, à ce que les activités menées par elles dans le cadre international aient des retombées dans les domaines d'intérêt concret pour la Belgique (tels que l'océanologie, la climatologie, la télédétection).

En tant que co-responsable de la Politique scientifique je suis pleinement conscient que, pour être menée à bonne fin, la recherche scientifique en général, et la recherche sur l'Antarctique en particulier qui fait intervenir de nombreuses disciplines, telles notamment l'écologie, la glaciologie, la géologie, la biologie et la climatologie, doit s'inscrire dans le cadre d'une action multidisciplinaire. La collaboration internationale est impérative si l'on veut aboutir au succès en matière de recherche scientifique sur l'Antarctique, étant donné les conditions extrêmes dans lesquelles elle se déroule.

Je me réjouis par ailleurs de constater qu'un important objectif du programme a été rencontré dans le sens où l'intégration active des unités de recherche belges au sein des équipes étrangères a pu être établie.

Het is in het licht van deze internationale samenwerking dat deze Nationale studiedag niet alleen tot doel heeft een overzicht te geven van de resultaten van het Belgisch onderzoekprogramma, doch tevens een overzicht te geven van de globaliteit van buitenlandse campagnes waaraan onze Belgische teams hebben deelgenomen. Ik maak hierbij van de gelegenheid gebruik om onze buitenlandse gastsprekers te verwelkomen en tevens te danken voor hun gastvrijheid en de inspanningen die zij zich getroost hebben om de Belgische onderzoekers op te nemen in hun campagnes.

De internationale samenwerking inzake Antarctisch onderzoek situeert zich niet alleen op het niveau van de uitvoering van de werkzaamheden doch eveneens op het niveau van de verspreiding van de resultaten. Dit is een facet dat ik als Staatssecretaris voor Wetenschapsbeleid enkel maar kan toejuichen. Het is immers belangrijk dat de kennis die verworven wordt door het onderzoek een brede verspreiding kent en een middel vormt om de nodige gegevens te verstrekken aan de beleidsmensen opdat zij de juiste maatregelen zouden nemen voor het beheer van het Zuidpoolgebied.

Deze studiedag werd om die reden tevens opgevat uit het oogpunt van de voorstelling van de resultaten van het Belgisch onderzoek aan de betrokkenen van andere verdragslanden. Ik hoop dat de vertegenwoordigers van de verschillende ambassades, die ik hierbij wens te danken voor hun aanwezigheid, dit initiatief kunnen appreciëren.

Het is mij duidelijk dat de resultaten van het huidig programma niet direct leiden tot een economische valorisatie voor ons land, doch dat het onderzoek thuishoort in het domein van de zuivere meer fundamentele wetenschappen. Anderzijds draagt de tenuitvoerlegging van een Belgisch Antarctica-programma ertoe bij dat onze delegaties met een voortreffelijke wetenschappelijke ondersteuning kunnen deelnemen aan de vergaderingen in het kader van het Antarctisch Verdrag. Het is tevens zo dat de kennis van de complexe fenomenen, zoals de voedselkringloop van de Zuidelijke oceanen en de dynamica van de ijskap en haar invloeden op het klimaat, niet in een korte tijdspanne kan opgedaan worden doch een doorgedreven onderzoekinspanning vergt.

Zoals U wellicht weet zijn zowel de Minister van Wetenschapsbeleid als ikzelf ervan overtuigd dat naast het toegepast en pre-industrieel onderzoek ook het fundamenteel onderzoek zeker niet mag verwaarloosd worden en de nodige steun moet krijgen. In dit licht en rekening houdend met het zojuist aangestipte karakter van het Zuidpoolonderzoek en de internationale samenwerking zal ik mij inzetten opdat dit onderzoek dat thans is aangevat ook na het einde van dit programma zou kunnen verdergezet worden. In de huidige economische context zal deze inspanning echter wel binnen de begrotingsperken van het huidig programma dienen te blijven. Dit zou ons de mogelijkheid bieden onze medewerking te handhaven aan de internationale wetenschappelijke activiteiten in het kader van het Antarctisch Verdrag. Tevens zou het echter onze onderzoekers toelaten deel te nemen aan de Europese samenwerking die recent tot stand is gekomen inzake poolonderzoek binnen het kader van de European Science Foundation en aldus de Belgische deelname in dit lovenswaardig Europees initiatief verzekeren.

Tot besluit hou ik er aan alle deelnemers een interessante en nuttige studiedag toe te wensen.

I. NATIONAL RESEARCH ACTIVITIES

THE BELGIAN SCIENTIFIC RESEARCH PROGRAMME ON THE ANTARCTIC : GOALS AND FIRST REALIZATIONS

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services – Science Policy Office

I. ABSTRACT

After a short historical review of Belgian scientific activities in the Antarctic, the objectives of the programme are presented. Antarctic research is aimed at acquiring the knowledge necessary to fullfil two important needs :

- to ensure the proper management of the environment and the natural resources of the Antarctic;
- to evaluate the global impact on our planet of the natural phenomena occurring in the Antarctic region.

In order to provide some answers to these problems four research fields have been selected : plankton-ecology, marine geochemistry, marine geophysics and glaciology-climatology.

The research topics taken into consideration in each of these areas are presented; furthermore a review is given of the research activities developed so far and of the first results obtained in the various fields of interest.

II. HISTORY

Belgium's interest in Antarctic research dates back to 1897. In that year, the "Belgica" left for the Antarctic, under the command of Luitenant Adriaan de Gerlache de Gomery. During the long stay, numerous observations and surveys were carried out on the spot.

The major points of interest can be summarized as follows :

- characterization of the gravimetric, astronomical and meteorological properties;
- study of the aurora polaris, glaciers, ice, seawater, fauna and flora and geology.

Between 1910 and 1936, the gathered data were studied, resulting in the drawing of charts, the tracing out of curves with regard to the magnetic field of the earth, the classification of 55 species of lichen and 27 of moss (previously, only 3 were known).

The decisive factor for internationally organized and sustained research and the further exploration of the Antarctic came about during the "International Geophysical Year" (1957–1958), a milestone in the history of research on Antarctica.

In the framework of this Geophysical Year, Baron Gaston de Gerlache de Gomery, son of the explorer who investigated the Antarctic in 1898, organized a new expedition to the Princess Ragnild Coast.

During this expedition, the King Baudouin Base was founded, later becoming the junction of the Belgian expeditions that followed.

From 1958 to 1961, there was an expedition every year. The main fields of research were : geodesy, geophysics, oceanography and photogrammetry. In 1967, the King Baudouin Base was definitely closed down. Ever since, Belgians participated only individually mainly in South African and American expeditions.

Following the growing international interest and research efforts in the Antarctic, a new research programme started in 1985. The following elements were taken into account :

- the considerable progress that has been made since the first expeditions, both scientifically and logistically;
- the priorities of the science policy and the budgetary restrictions of our country.

III. RESEARCH GOALS

The way it is presently conceived, the scientific research programme on Antarctica is aiming at acquiring the necessary knowledge in order to meet two major needs.

In the first place, there is the need to guarantee the rational management of the environment and of natural resources of the Antarctic and in particular the preservation of this environment which is highly vulnerable for possible human interventions.

The good management of this environment calls for a thorough knowledge of the dynamics, the present contamination of the ecosystem and the possible consequences of increasing pollution. Moreover, the exploitation of renewable resources (krill, fish, squids), has to be kept under control so as not to disturb the natural balance of the populations, which supposes continuous scientific assessment of the consequences of the exploitation.

Next to this, there are still a number of gaps with regard to the knowledge of the type, the structure and the origin of the sediments of Antarctica. Nevertheless there are signs of the presence of non-renewable resources (minerals, petroleum, gaseous hydrocarbons). The possible consequences of their eventual exploitation should however being known.

Research should thus aim at providing the necessary arguments to allow policy-makers to take the right measures, and to ensure that Antarctica is going to be safeguarded against irrational exploitation and would, in such a way, be exposed to pollution like the rest of the world.

The second major need, requiring the acquisition of knowledge, consists of assessing the consequences for our planet of natural regional phenomena such as thermal exchange with the surrounding oceans and continents, the formation of deep water, the dynamics of the ice cap, etc ...

The Antarctic and the surrounding ocean play indeed an important role in the climate's regulation on earth. On one hand, the enormous ice cap plays the role of a cold-source and on the other hand the Southern Ocean plays a major role in the global circulation of the world oceans. Studies of the interactions between the atmosphere, the oceans and the ice cap, as well as the glaciological and climatological studies in this field should allow to extend knowlegde with regard to the impact of this continent on the world climate and the atmospheric conditions. Besides that, they should provide a guideline so as to determine the origin and to assess the consequences of possible changes that may occur (e.g. increase in the CO_2 concentration, ozone-hole).

IV. FIELDS OF RESEARCH

In order to meet the two-fold problem outlined above and taking into account the priorities that have been identified by the international scientific community, four fields of research have been adopted.

Plankton ecology

The field of plankton ecology is going to deal with three complementary topics, aiming at contributing and improving the knowledge of the global functioning of the basis of the trophic chain of the marine Antarctic environment.

In the first place, the research deals with the study of the nutrition mechanisms of phytoplankton in relation to the physical and chemical parameters of the environment as well as the role of heterotrophic micro organisms in the recycling of organic matter. This research is based on the measurement of the biochemical composition, the metabolical activity, the biomass and the production of phyto- and bacterioplankton. The zooplankton represents the third trophic level considered in this approach. The study of it deals with its nutritional activity and in particular with the metabolic mechanisms that are responsible for the accumulation of lipidic reserves.

Moreover, research on plankton ecology implies the assessment of reference levels of contamination, both in seawater and in plankton organisms, with regard to toxic substances such as stable organochlorine residues and mercury. The mechanisms for the transfer of these pollutants are also taken into consideration.

Marine geochemistry

In the field of marine geochemistry, it is envisaged to contribute to improving the knowledge of the biogeochemical cycle of the trace elements in the Southern Ocean. Barium has been chosen as standard trace element for this study.

Marine geophysics

The objective of the research developed in the field of marine geophysics, is to fill certain gaps that still exist in the knowledge of the structures and of the genesis of the sediments of the continental platform from Antarctica. To this end, the application of seismic reflection is called in, the techniques of which allow to establish the deformation structures and the succession of geological formations with a very high resolution.

Glaciology–climatology

In the field of glaciology–climatology, four themes have been selected. They deal with the interactions between ocean, ice and the atmosphere in relation with their climatological implications. This research is to a great extent calling in the development of mathematical models.

The first theme relates to the study of the isotopic composition of ice. The object of this study is to lay down a method for assessing the original isotopic composition of ice, with a view to being able to reconstitute the prevailing climatic conditions at the time of their formation. This method is also developed so as to assess the formation speed of ice.

The phenomenon of periodical extension and retreat of the sea–ice represents one of the most striking properties of the Southern Ocean. The evolution of these ice fields is still poorly known, and it would be interesting to be able to forecast on this evolution. Two research teams have been instructed to develop a mathematical model for the description of the evolution of the sea–ice throughout the seasons, taking into account the interactions between ocean and atmosphere, ocean and ice, and atmosphere and ice.

A third theme aims at devising a model of interaction between the thickness of the ice–cap, the glacier flow and the variations of the sea–level.

The fourth theme pays attention to studying the dynamics of heat exchanges and their effects on the formation of deep water bordering on the continent. In order to assess the impact of these phenomena on the climate, a mathematical model is developed, describing the interactions between, on one hand, the sea–ice and the formation of deep water, and on the other hand, the formation of katabatic winds.

V. ACHIEVEMENTS

Because of the long interruption of Antarctic research, the scientific activities were in the first place concentrated on :

- the analysis of specialized literature;
- the elaboration of methods for the analysis and measurement of the specific environment of the Antarctic;
- finalizing the methodology of laboratory experiments and experiments on the spot;
- the drawing up of mathematical models.

So as to achieve the stipulated aims, the scientists and the operational direction of the programme collectively made contacts with countries who dispose of the necessary logistic means to equip Antarctic expeditions. Thanks to these actions, it was possible for thirteen Belgian researchers to participate during the Antarctic summer of 1986–1987, in the framework of the programme, in campaigns of Australia, Japan, the Federal Republic of Germany and France, that way allowing them to study physical, chemical, biological and geological aspects of Antarctica on the spot.

The travel route of the different expeditions is given in Fig. 1.

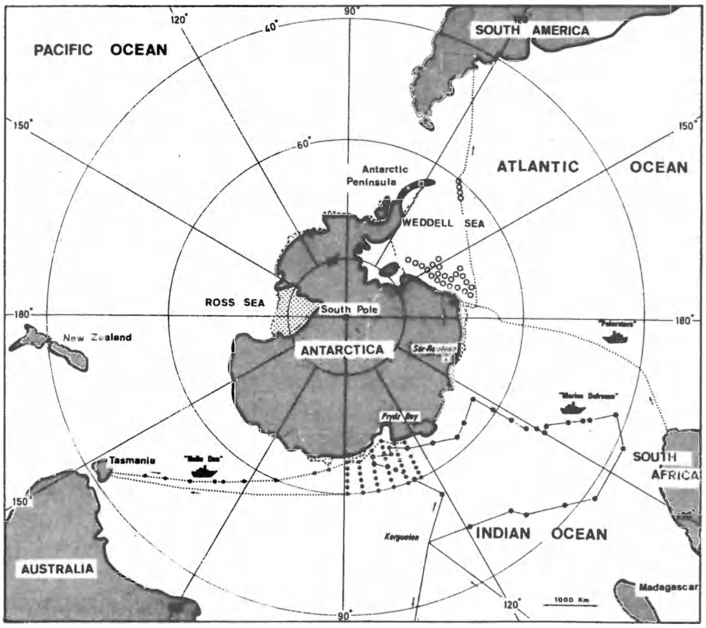

Figure 1 : Travel route of the different expeditions in which Belgian scientists of the programme participated during the 86–87 austral summer.

In the field of planktonecological research, samples were taken during the expedition, including seawater, phyto– and bacterioplankton and material in suspension. This was carried out over distances of several thousands of kilometers. Different analyses were carried out on these samples, in particular nutrient concentration in seawater, biochemical composition of bacterio– and phytoplankton, cholorophyll content of phytoplankton, growth rates, respiration and content of organochlorine compounds. Besides this, physical and non–biogenic chemical parameters of the seawater were measured.

On the basis of these analyses, it was possible to determine the influence of diverse parameters such as the hydrodynamics of the watermasses, temperature, light penetration, density and availability of nutrients on the distribution of the phytoplankton biomass. Usefull information was also gathered concerning the relation between the importance and the presence of phytoplankton in relation to bacterioplankton. Finally, knowledge has been acquired with respect to the pollution level of the marine Antarctic ecosystem, in particular by polychlorobiphenyls.

On the basis of measurements of the biogeochemical activity of the watermasses and the analysis of water samples, a concentration gradient of barium was observed which varies both in relation to the water depth and the degree of latitude.

The marine geophysical research has been carried out by means of the seismic measurements over a distance of 3,000 km. This allowed the analysis of the sedimentary structures and different aspects of tectonic deformations of the eastern and southeastern Weddell Sea.

With regard to glaciology-climatology, a computer model has been devised. Based upon the analysis of the isotopic composition of ice, the freezing speed was determined. The operational validity of this model has been experimentally checked.

Furthermore, numerical models have been developed and adapted for the description of the melting and freezing phenomenon of pack ice, the regional circulation in the atmosphere and the ocean and the changes in volume of the ice cap. These models have been validated with field data (Weddell Sea, ice cap, Adélie Land). Field data were also gathered with regard to the thickness and the type of ice layers and a network was set up for measuring the movement of glaciers in the Sör Rondane.

It is obvious that this brief survey of the results only constitutes the tip of the iceberg of what has been realized. More details on the activities and results of the research programme are provided throughout this volume.

To conclude, it can at any rate be put that considerable progress has been made in diverse research fields. Knowledge is acquired on a level that can bear comparison with the international Antarctic research. Moreover, the studies have been integrated in foreign programmes and close collaboration has come about, which can but provide added value to this research.

AUSTRALIAN ANTARCTIC RESEARCH - NOW AND IN THE FUTURE

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

AUSTRALIAN ANTARCTIC RESEARCH

ABSTRACT

The Australian Antarctic Division has the prime responsibility for maintaining Australia's activities in Antarctica. It is supported in its scientific role by a number of other government and non-government organisations which together comprise the Australian National Antarctic Research Expeditions (ANARE). The Antarctic Division undertakes research in glaciology, terrestrial and marine biology, upper atmosphere physics, cosmic ray physics, medicine, and psychology. These programs are conducted from our wintering stations of Davis, Casey, Mawson and Macquarie Island and a series of summer stations. Field programs are maintained through long range tractor traverses and by helicopter. We operate over 4000 km of the Antarctic coast using two ships and six helicopters. This year 131 scientists will travel to Antarctica while many others will remain in Australia working on the results of last years Antarctic program.

Geology and geophysics are undertaken in the vicinity of year-round stations and our summer bases. Programs aim at producing modern geological maps and conducting detailed research into the origin of the development of the Antarctic shield.

AUSTRALIAN ANTARCTIC RESEARCH

Meteorological data gathering is conducted at all year-round stations to provide input for Australian contributions to the World Meteorological Organisation, to aid Australian weather prediction and to assist operations in Antarctica.

Meteorological data is also gathered at all summer bases and from our ships.

Our Cosmic Ray Physics is concerned with variations of cosmic ray particle intensity.

The combined surface-and-underground installation at Mawson operates within an international network of cosmic ray observatories.

The Mawson facility plays a key role in bi-hemisphere investigations. It includes the only high energy installation at polar latitudes, and the main telescope, 11 metres underground is now the largest of its kind in the Southern hemisphere. The 11 metres of rock covering the telescope shield its counters from the low energy particles, which are recorded separately at the surface.

This high energy telescope enabled us to discover an important new phenomenon in cosmic ray modulation. It was the first major discovery in this field in the past 15 years.

The Upper Atmosphere Physics research program contributes to an understanding of the interaction between the solar wind and the earth's magnetic field and magnetosphere; the mechanisms that control the composition, the structure and dynamics of the upper atmosphere; the response of the upper atmosphere to natural and man-made disturbances; the coupling between lower and upper atmosphere and the role of the upper atmosphere in relation to climate and weather.

Optical measurements of certain phenomena have been made at Davis station during 1987 to determine seasonal and daily variations in the temperature between 80 and 90km altitude and to determine the extent of auroral influences on the region.

The advent of satellites transmitting in the VHF and SHF ranges has not, as had been expected, solved the problems of signal transmissions without ionospheric imposed disturbances and research continues into the problems.

In Glaciology, the common theme addressed by the Division's broad range of projects is the interaction of the Antarctic ice sheet and surrounding sea ice with the global environment, including the physical processes involved in that interaction.

Significant advances have been made during 1986/87 in several aspects of the program. A 234m deep ice core was recovered from a high accumulation area of Law Dome, a self-contained ice cap adjoining the main ice sheet, providing samples for detailed measurements of past atmospheric levels of the so-called "greenhouse" gases, and a test of some of the equipment and procedures to be used in the forthcoming deep drilling program.

The oversnow traverses made out of Casey have been a major field program and provide a substantial Australian contribution to the International Antarctic Glaciological Project. The major traverse routes established out of Casey span an area of over one million square kilometres of the interior of the ice sheet.

Shallow snow cores, up to 40m depth, are used to investigate the processes related to transformation of snow to ice and the development of the crystal structure found within the ice sheet, to establish the starting conditions for characteristics observed in the deep ice cores, and to provide basic "ground truth" information used in the interpretation of remote sensing data obtained from satellites.

Analyses of the physical properties of these cores are currently being used to provide a means of dating the deeper ice cores.

The laboratory study of ice mechanics aims at gaining an improved knowledge of small scale factors which influence the flow of ice masses.

Data on surface climatology, the processes of ice sheet-atmosphere energy exchange and katabatic wind flow over the Antarctic interior are obtained via satellite from automatic weather stations. Five automatic weather stations operated during the last year.

A Deep Ice Drilling program is now well underway after the first year of its approximate five year plan. Its aims are to drill and extract a 1200m ice core to bedrock near the summit of Law Dome and to analyse the core for its historical record of environmental and geophysical information. The Law Dome drilling will test the mechanical coring system's capability of drilling 4500m through the ice sheet further inland; a program we hope to commence within 4 years.

A recent research program has revealed a 500 year record of the atmospheric "greenhouse" gases carbon dioxide, methane and nitrous dioxide. Concentrations of chlorofluorocarbons will soon be measured. New core is now being similarly analysed. Its overlap with modern, direct air measurements should confirm the accuracy of the analysis.

Oxygen isotope ratios reveal climatic records and annual cycles of accumulation in ice cores. Measurements on shallow cores taken during inland traverses are being used to investigate variations in snow accumulation. The climatic record of the last few hundred years is being refined.

Data on the size and distribution of icebergs in the Southern Ocean continues to be collected on all resupply and research voyages. Observations made during the 1986/87 season allowed the seasonal change in iceberg numbers to be determined and suggested that once icebergs are in open sea, free of the seasonal pack ice, they break up in only a few months. This has implications for the conjectured schemes for using icebergs as a freshwater resource.

Vertical aerial photography of most of Heard Island was obtained with a helicopter mounted 70mm camera in the 1986/87 summer. The photography will be used to map the glaciers of Heard Island and as a base for monitoring changes in their extent.

Biology

Our biological projects focus on both the marine and terrestrial ecosystems.

During 1986/87, the emphasis in Marine Science continued to be directed towards gaining an understanding of the Antarctic marine ecosystem. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has designated our main study area, Prydz Bay, as one of the study sites for its ecosystem monitoring program. Much of our past and future work, in conjunction with elements of the total Biology Program, has been, and will continue to be, relevant to this program.

The main component of the program continues to be studies of the Antarctic krill, *Euphausia superba*, a key component in the food web. Field work consists of regular surveys with nets and acoustic equipment to assess its distribution, abundance and life history in the study area, and these are complemented by laboratory studies on age and growth, physiology and feeding behaviour. The Antarctic Division was the first laboratory in the world to raise krill in the laboratory from eggs to spawning adults, and in the process discovered much about this animal which is so difficult to study in the wild for most of the year. Some of our laboratory krill have been living in our lab for 6 years after coming in as mature adults.

A study of the distribution and abundance of krill will continue to be undertaken to contribute to the 'rational' management of the resource.

Phytoplankton are studied as food for krill and non-krill zooplankton. The physical and chemical properties of the seawater are also studied in order to try to explain and or predict the behaviour of the organisms.

The major activity this year has been a marine science cruise to the Prydz Bay area in February to April 1987. The main aims were to conduct a study of the bottom-living fishes of the Bay and the larval ecology of krill. Additionally, an intensive study of phytoplankton and bacterioplankton was accomplished, and oceanographic data taken. This program included two Belgian scientists.

Offshore marine research was undertaken around Macquarie Island for the first time. A short program to study the fish fauna was completed during a station resupply trip. Several species were recorded at the island for the first time, and a much clearer understanding of the fauna and its relationships has been achieved.

Activity has also increased in the waters around Heard Island, where Australia claims an Exclusive Economic Zone. The Soviet Union and Australia agreed to a joint fisheries research cruise in that Zone last season and the Antarctic Division placed an observer aboard the Soviet research vessel.

During 1987/88, field work will focus on physical and chemical oceanography in the Prydz Bay and Commonwealth Bay areas, and on a survey of Crabeater seals.

Approximately 30 strains of Antarctic phytoplankton were isolated into culture by University of Tasmania participants following the 86/87 voyage. These will be used in ecophysiological experiments, to determine the response of growth rate to temperature, and to light and nutrient concentration.

Collaboration with the University of Brussels will continue in 1987/88 on the planned Antarctic Division transect from Hobart to Commonwealth Bay. The abundance of phytoplankton, bacteria and protozoa will be measured and correlated with the various oceanographic conditions encountered in order to determine the patterns of production, and utilization of organic matter, at the base of the food chain.

The oceanographic program has focused on providing a description of the broad characteristics of the water circulation within and to the north of Prydz Bay.

The principal areas of terrestrial biology research include a continuing investigation of the aquatic habitats of the Vestfold Hills region. They also include seals, penguins and other birds, as predator species, particularly in the Prydz Bay region. Botanical investigations of the environs of Casey station are another major program.

Intensive laboratory culture studies of mosses, carried out in 1986, concentrated on the effect of environment on growth form. The mosses show different responses to variations in composition of growth media, particularly to nitrogen.

HUMAN BIOLOGY AND MEDICINE

The objectives of Australia's Antarctic Human Biology and Medicine program are:

- to gain an understanding of the effects of the Antarctic environment on man;
- to take advantage of the special opportunitites provided by Antarctica for medical research.

With recent research suggesting expedition personnel in Antarctica are subject to greater psychological disturbance than has previously been supposed, the following areas of research are being carried out:

- investigation of the depression of the immune system of winterers, including photobiological studies;
- endocrine activity and its interaction with the environment;
- stress and behavioural adaptation;
- inter-related studies on nutrition, stress and cardio-vascular status of personnel;
- microbiology;
- epidemiology; and
- occupational health.

Psychological research is concentrating on determining the personal characteristics required to give the greatest probability of people being good community members, an important criterion in overwintering, and on methods of overcoming interpersonal problems in isolated communities.

AUSTRALIAN ANTARCTIC RESEARCH

INTERNATIONAL COLLABORATION

Australia has played host for several years to year round presence of scientists from the People's Republic of China, in the disciplines of glaciology, physics and terrestrial biology.

The summer programs have been more diverse than winter and the numbers of international visitors much greater. Visitors last summer were from Belgium (marine biology), West Germany (geology), Austria (geology), Sweden (geomorphology), Spain (ornithology), Japan (geophysics) and the Netherlands (ornithology).

International coordination through the Scientific Committee on Antarctic Research (SCAR) is a critical element of such programs as the International Antarctic Glaciological Program (IAGP), Biological Investigation of Marine Antarctic Systems and Stocks (BIOMASS), Evolution of Cenozoic Palaeoenvironments of the Southern High Latitudes and so on. Much marine biology is now organised under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), a convention developed under the umbrella of the Antarctic Treaty and which has its headquarters in Hobart, the city in which the Australian Antarctic Division is based.

THE FUTURE

In Australia's future Antarctic research programs we will see an emerging emphasis on environmental research and on research directed towards the conservation of the Antarctic marine ecosystem. We expect to have a new marine research vessel in operation in two years. This vessel will have a greatly increased research capacity over our current vessel. More time will be scheduled for marine science and commercial scale trawling will be undertaken with the objective of monitoring variations in the stocks of fish and krill.

I look forward to continuing international co-operation in Antarctic research.

BRITISH ANTARCTIC SURVEY ACTIVITIES WITH SPECIAL REFERENCE TO GLACIOLOGY

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services – Science Policy Office

BAS GLACIOLOGY

KEYWORDS: ANTARCTIC, GLACIOLOGY, LOGISTICS, POLLUTION

ABSTRACT

BAS supports six science divisions covering the Atmospheric/Space Sciences, Life Sciences and Earth Sciences. Glaciology is a mainstream discipline within the Ice and Climate Division. Logistics support is provided through the Antarctic research stations (Bird Island, Signy, Faraday, Halley and Rothera, the latter being the principal focus for the deployment of glaciological field parties), aircraft (BAS operates three ski-equipped Twin Otter aeroplanes) and ships (RRS Bransfield and John Biscoe). The glaciological research is directed into two principal programmes: the Dynamics of the West Antarctic Ice Sheet and Past Climate and Environment. Current work on the Ronne Ice Shelf is concerned with the dynamics of the ice sheet system (inland ice - ice streams - ice shelves). The aim is to understand how the forces which restrain ice sheet flow react to changing boundary conditions in a changed climate. Survey stations have been established on the Ronne Ice Shelf and the Rutford Ice Stream to determine velocities and strain rates. Radio echo sounding data are also being used in conjunction with satellite imagery to decipher the physical mechanisms that control the movement of the fast flowing Rutford Ice Stream over its bed. Data are being used in the development and testing of ice sheet models. BAS glaciologists are investigating the thermal regime of temperate George VI Ice Shelf. The aim is to produce estimates of basal melt rates over the entire ice shelf and understand the physics of the processes which control their behaviour. The work involves drilling through the ice to measure temperature gradients and install instruments in the sea beneath the shelf, and oceanographic studies of the surrounding waters.

The response of the ice sheet system to past climatic change can be studied using chemical data from ice cores. BAS glaciologists have concentrated on shallow cores from the Antarctic Peninsula which give climatic information over the past 50 years which can be compared with meteorological records. This has produced improved knowledge of the relationship between stable isotope composition and air temperatures. In the future deeper cores will be drilled in Palmer Land. Global pollution is being studied by investigations of heavy metals in recent snow and comparison with older ice in which concentrations are being determined at the pg/g level.

1. INTRODUCTION : THE BRITISH ANTARCTIC SURVEY

The British Antarctic Survey (BAS) is responsible for the British Government's scientific research activity in the Antarctic, South Georgia and the South Sandwich Islands and covers a land area of some 1.1 M km^2 (Figure 1). The

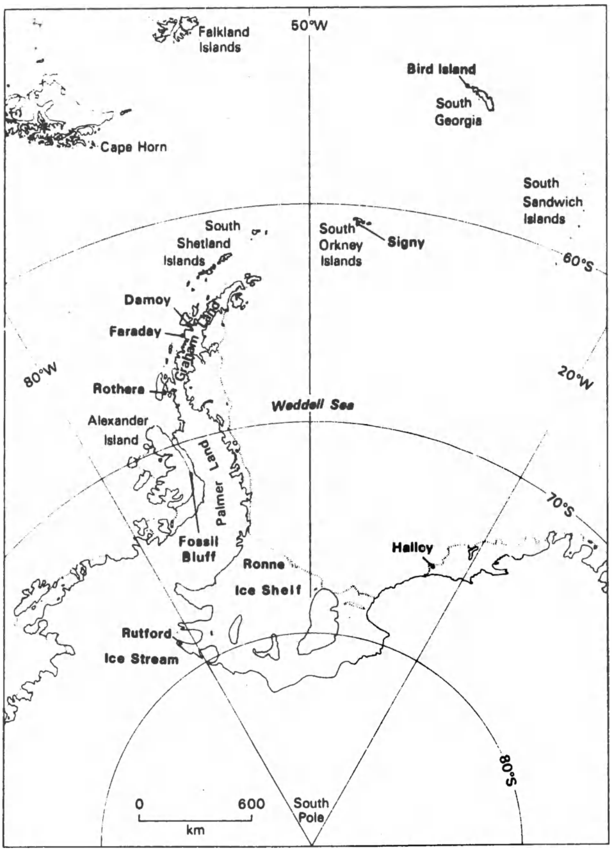

Fig. 1.
Location map for activities of British Antarctic Survey.

Survey originated as a wartime naval operation (Tabarin) in 1943 which was transferred to the Colonial Office in 1945 and was known until 1962 as the Falkland Islands Dependencies Survey. In 1967, BAS became one of the research institutes of the Natural Environment Research Council (NERC). Financial support comes through NERC from the Department of Education and Science. The total scientific and support staff totals about 400, made up of contract personnel supervised by BAS permanent staff. The Survey currently runs on an annual budget of £15 M excluding major new capital expenditure on ships, aircraft or Antarctic bases.

2. ORGANIZATION OF SCIENTIFIC RESEARCH AND LOGISTICS

Research is organized from the BAS headquarters in Cambridge within the framework of six scientific divisions - Geology, Geophysics, Upper Atmospheric Sciences, Ice and Climate, Terrestrial and Freshwater Life Sciences and Marine Life Sciences. In addition, a seventh division is responsible for administration and logistics - co-ordinating the supply and rebuilding of Antarctic stations, air and ship operations, staffing and finance.

BAS maintains five permanently-manned stations (Figure 1). Bird Island is located in the sub-Antarctic off the western tip of South Georgia. It is the smallest station with a summer complement of 8 scientists and 3 overwintering personnel. Research is focussed upon the biology of the higher predators of the Southern Ocean ecosystem - the numerous birds and seals which frequent the islands. Signy Island in the South Orkney Islands also concentrates on a wide range of biological research, principally marine, freshwater and terrestrial programmes. Upwards of 30 persons may work at Signy during the summer. BAS maintains two research stations along the west coast of the Antarctic Peninsula, the most southerly is at Rothera on Adelaide Island. This is the centre for extensive earth science operations supported by aircraft and has a summer complement of 70. Geological, geophysical and glaciological programmes are deployed from Rothera to field camps or advance summer-only bases such as Fossil Bluff on Alexander Island. Faraday is a geophysical observatory undertaking work on geomagnetism and upper atmospheric physics. The latter is also the principal activity at Halley, the most remote BAS station at 75°S and located on the floating Brunt Ice Shelf in the south-eastern Weddell Sea.

The bases are re-supplied each year by two BAS vessels, the RRS Bransfield and RRS John Biscoe. The Bransfield is the larger of the two at 100 m length and ice-strengthening allows her to enter the pack ice of the Weddell Sea to reach Halley. John Biscoe was modified in 1979 to undertake scientific cruises for about 100 days each year, principally in support of marine geophysics and geology and the Offshore Biological Programme. Built in 1956, she is to be replaced in the 1990-91 season by a new dual role (science/cargo) ship of about 95 m length.

Three ski-equipped de Havilland Twin Otter aircraft (a fourth will be acquired in 1988) are used to deploy scientists to field camps and bases, operating out of Rothera, where a snow/ice runway is maintained, and undertake a variety of remote sensing projects - radio echo ice thickness sounding, aeromagnetics and aerial photography.

3. GLACIOLOGICAL RESEARCH

The BAS supports a large scientific Division to investigate glaciological and related climatic phenomena, recognizing that ice plays a major role in the global ocean/atmosphere system. Antarctica, still firmly in the grip of an ice age, provides a useful analogue for the ice sheets that covered northern continents 12,000 years ago. The size of the ice sheet is regulated by climate, and one of the key unsolved questions concerns the response of the ice sheet to climate change induced by human activity - especially the greenhouse warming effect. The investigation of the issues associated with this problem are of prime concern to BAS and have led to the development of two principal research programmes.

3.1 Dynamics of the West Antarctic Ice Sheet

The West Antarctic ice sheet, which rests on bedrock below sea level, is believed to be particularly vulnerable to climate change and could shrink significantly over periods as short as a few centuries, leading to significant rises in sea level world-wide, with consequent social and economic damage.

A strategic BAS programme is looking at all the active elements in the ice sheet system (the inland ice sheet, outlet glaciers/ice streams and floating ice shelves) with the aim of producing a coherent account of the interactions between each of the different parts. Each element has its own distinctive set of boundary conditions and physical processes that govern its flow, but they must all be coupled together in a realistic fashion to understand present day behaviour and to predict consequences of any changes in the environment.

3.1.1 Ronne Ice Shelf - Rutford Ice Stream - flowline study

Rutford Ice Stream drains about 36,000 km^2 of the West Antarctic Ice Sheet into Ronne Ice Shelf (Figure 2). The BAS have been operating over the drainage basin, ice stream and adjacent ice shelf since 1975 in a variety of groundbased and airborne surveys.

In the 1985/86 season, a line of survey stations was established along a flowline on Ronne Ice Shelf, one of the two largest ice shelves in Antarctica (Figure 2). Some of these stations were remeasured in the 1986/87 and 1987/88 seasons using satellite positioning as well as optical survey equipment, to give values for ice velocity and strain rates. Additional stations were established to continue the line to the ice front. Already, it is possible to refine estimates of the basal melt rates (Doake, 1987; Jenkins and Doake, in press). It appears that within 150 km of the ice front there is a zone where saline ice is frozen onto the bottom of the ice shelf but is melted off before

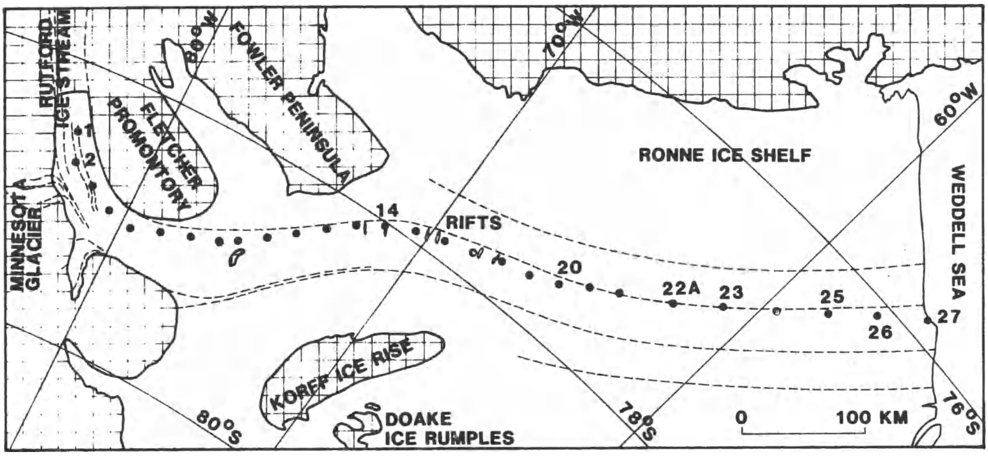

Fig. 2. Position of Glaciological Survey stations on Ronne Ice Shelf.

the ice front is reached. Ground based and airborne measurements show variations in the strength of basal radar reflections which support these results. After the flow has been successfully described by a realistic kinematic model, other estimates of physical quantities can be made, such as the forces acting on the ice shelf.

The inland end of the BAS ice shelf network joins a more intensive survey network on Rutford Ice Stream. Stake networks covering more than 140 km extend along an approximate flowline and across a grounding line that has been located on the downstream side of a small knoll by using tiltmeters to measure tidal flexure of ice more than 1600 m thick (Stephenson, 1984). The networks have been surveyed for velocity and strain rate and sounded by radar for ice thickness (Stephenson and Doake, 1982; Doake et al., 1987). Rapid variations in radar echo strength from the basal layers contain information about the nature of the glacier bed and the possible distribution of water pockets. Patterns of echo characteristics can be compared with surface topography seen in satellite images and with velocity and strain rate data from the survey network. Correlations will help understand the physical mechanisms that control the movement of a fast flowing glacier over its bed (measurements show that Rutford Ice Stream moves at a surface rate of between 300 m a^{-1} and 400 m a^{-1}), and a subset of the survey data has been analysed to see how the various forces acting both to drive and to restrain the ice stream vary with distance from the ice shelf junction (Frolich et al., 1987). For example, flow of the ice stream over a bedrock step of 500 m has created a surface knoll, which is seen clearly in satellite images. The force arising from vertical shear stress gradients is important within distances of a few ice thicknesses of the step (ice thickness about 2000 m), and represents a 'bending' component. The local peak in the driving force seen as the ice flows over the knoll is apparently absorbed by this 'bending' term. It is also noticeable that the flow must be explained by a full three dimensional analysis; lateral strain rates increase several kilometres upstream of the surface knoll, showing diverging flow around the bedrock step.

The ice stream under investigation is a transition region between the inland ice sheet and the ice shelf. Whether this is a stable configuration, or whether a periodic oscillation occurs, perhaps triggered by internal flow dynamics or external climatic forcing, is a fundamental problem in the interpretation of the dynamic history of ice sheets. Satellite remote sensing data are also assisting investigation of these problems. For instance, comparison between a SPOT image taken on 8 January 1987 (Figure 3) and a Landsat image of 3 February 1974 shows that surface topographic patterns on

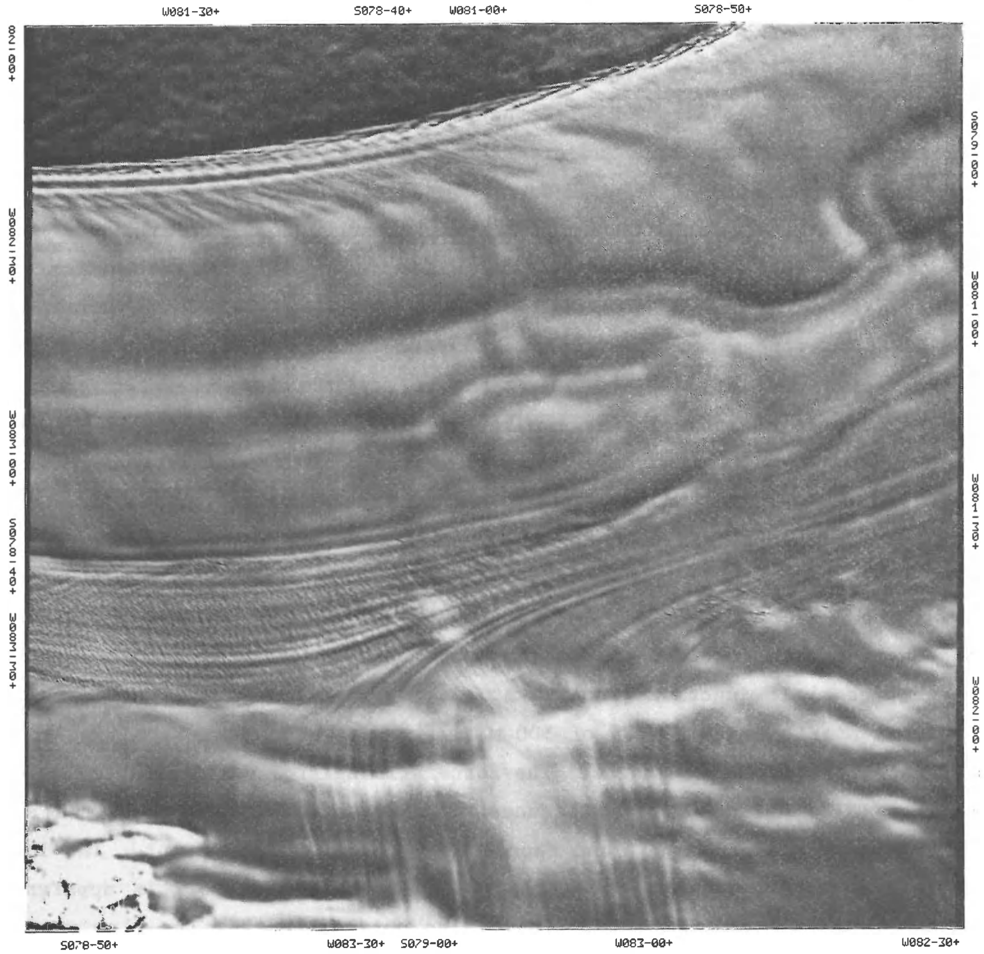

Fig. 3. Image of Rutford Ice Stream © CNES 1987 from SPOT satellite, 8.1.87. The ice is flowing from left to right in approximately south-easterly direction. Surface patterns are caused by subtle topographic relief, with height differences up to 20 m over distances of a few km.

Rutford Ice Stream have been displaced downstream by several kilometres (Vaughan, Doake and Mantripp, in press). Ice velocities derived from these movements agree with measurements made by ground based surveys in the near vicinity. Because the surface topography is thought to reflect partial grounding of the glacial sole the implication is that the substrate to the ice stream is mobile. Deformable beds to glaciers, composed of water-saturated till with effective pore pressures of near zero, have been suggested by Boulton and Jones (1979) and recognized in seismic records on Ice Stream B in Marie Byrd Land by Blankenship et al (1987). However, this is the first time that movement of a glacier bed on such a large scale has been seen and this has important implications for the dynamic behaviour of the ice stream and its reaction to climatic changes. Pixel radiance values from the SPOT images have been compared with surface slopes measured along a detailed level line by a ground based survey in February 1987. There is a strong relationship between slope and radiance, suggesting that our goal of deriving quantitative topographic data from single SPOT images is attainable.

Although a number of Landsat images of Rutford Ice Stream were acquired in 1973 and 1974, it is only fairly recently that some have been digitally enhanced by B. K. Lucchitta of the U.S.G.S. (Swithinbank and Lucchitta, 1986). The surface relief on the ice stream is only of the order of 20 m over distances of several kilometres, but the uniformity of the snow surface albedo again means that the radiance measured by the satellite sensor depends mainly on surface slope.

3.1.2 Ice Shelf - Ocean Dynamics

George VI Ice Shelf, on the west coast of the Antarctic Peninsula, is unusual: unlike other ice shelves which are underlain by sea water barely above freezing the sea water here is up to three degrees above freezing. BAS glaciologists are studying the thermal regime of George VI Ice Shelf together with the oceanographic circulation beneath it. The results are important in modelling what might happen should warmer water, in a warmer climate, freely intrude beneath all ice shelves.

The channel of George VI Sound is typically 700 m deep and is overlain for most of its 500 km length by an ice shelf of around 100 m thickness at the northern ice front, increasing to 500 m thickness to the east of the Eklund Islands. Profiles of temperature (T) and salinity (S), measured in the vicinity of the northern ice front (Loynes *et al.*, 1984; Potter *et al.*, 1985) show a linear T/S dependence, confirming a thermodynamic model of ice melting in Circumpolar Deep Water and indicate that thermohaline convection is the principal mixing process. Oxygen isotope profiles demonstrate that the melting ice has a value of -20°/oo with respect to Standard Mean Ocean Water (SMOW). This is similar to the mean isotope ratio of present-day accumulation in the catchment (Potter and others, 1984). Since the basal ice is formed from accumulation over several millennia, it seems that there has been no significant net climatic change in the Antarctic Peninsula over this period. Measurements support a simple circulation model for the northern part of George VI Sound; Circumpolar Deep Water is advected under the ice shelf at depth, upwells transferring heat which melts the ice and then collects in a northward outflow gathered to the west by Coriolis force. The circulation is driven by the melting process which causes the upwelling of warmer water from greater depths.

Potter and Paren (1985) have inferred from T/S profiles that the northern circulation penetrates at least 160 km south but not so far as the southern ice front in the Ronne Entrance. These geographical limits constrain the basal melt to values between 1.1 and 3.6 m a^{-1}. If the ice shelf is in equilibrium it alone supplies 53 km^3 a^{-1} of ice melt or about one-sixth of the total for Antarctica.

Pedley and others (1986) have measured a year-long tidal record from beneath George VI Ice Shelf. An unusual feature of the record is a significant response in tidal species 3 to 7. Nonlinearity also occurs in the tidal motion of the Ronne and Ekstrom ice shelves but has not been reported from the Ross Ice Shelf. The tidal dynamics of several Antarctic ice shelves have therefore been modified by a region of strong nonlinear response to tidal forcing and an anelastic component in the deformation of the ice at the grounding line is tentatively proposed as the mechanism responsible.

Talbot (1987) has assembled all the available hydrographic evidence to discuss the oceanic environment of George VI Ice Shelf, and has prepared a 2800 km-long section illustrating the temperature, salinity and density structure of the sea. The transect embraces the ice shelf and extends through both its ice fronts and across the continental shelf breaks into the deep Pacific Ocean. This is an important contribution to knowledge of the oceanography of the warm Pacific sector, since hitherto all hydrographic sections have terminated at the shelf break because sea ice has curtailed shipboard surveys.

3.2 Past Climate and Environment

The Antarctic ice sheet has preserved a record both of its own evolution and of the changing climatic regime under which it is developed. The ice sheet consists of a continuous sequence of annual layers of snow, in places several kilometers thick, spanning up to several-hundred-thousand years of the Earth's history. Each layer preserves a sample of the atmospheric gases and dusts in the atmosphere at the time of the original snowfall. Analysis of the physical and chemical properties of the ice yields evidence on past climate, on factors that may have forced climatic change, on the size of the ice sheet, and in the upper part direct evidence for global pollution and human impact. Interpretation of this unique and highly detailed record is yielding quantitative information which will enable a rigorous test of computer models describing the evolution of the ice sheet, and is providing vital input data to the GCM's that are being developed for long term climate prediction.

Ice core studies are a focal point of BAS glaciological research. They aim to reconstruct the climatic history of Antarctica, both as an essential step towards understanding global climatic processes and to test theoretical models that can predict future climatic change. Furthermore, they aim to achieve a detailed record of global air pollution, revealing the importance of a human impact on the global environment.

3.2.1 Past Climate

BAS studies are presently concentrated in the Antarctic Peninsula, which cuts across the sub-Antarctic zone, bridging all the 1000 km of the gap between South America and Antarctica. It is uniquely placed to relate climatic records from the continental ice sheet with the glacial and climatic history of lower latitude continents.

The BAS effort takes advantage of the relatively long instrumental records of climate available from the region, to explore the transfer functions between climatic and ice-core parameters and essential for reliable interpretation of deep ice-core data. Studies (Peel and Clausen, 1982; Mumford and Peel, 1982) of stable isotopes, mineral dusts and dissolved salts have been made in more than 30 mainly hand-drilled, shallow cores from many parts of the region (Figure 4). They show that large areas of the Peninsula have preserved a rich geochemical stratigraphic record of climate with a regular, accurately dateable succession.

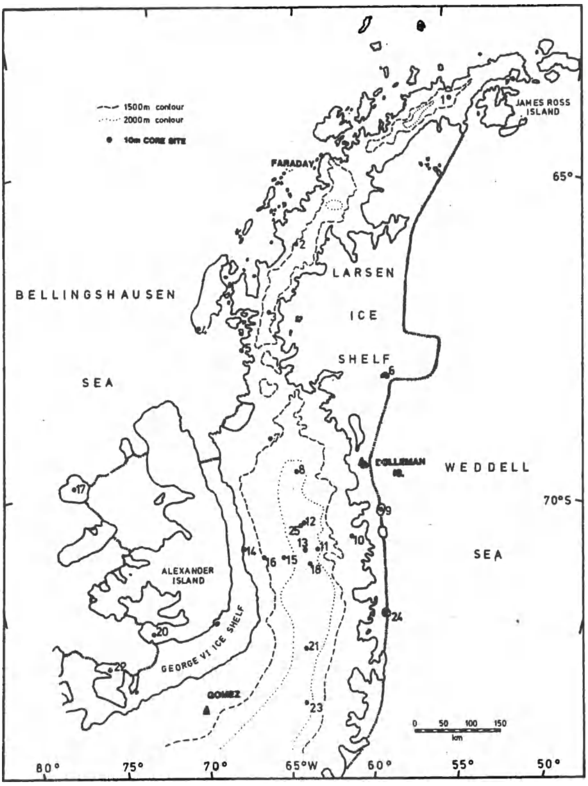

Fig. 4. Map of the Antarctic Peninsula showing the location of drilling sites and weather stations cited in this paper.

Two electromechanically-drilled cores have so far been drilled at sites chosen to represent the two principal climatic zones of the region; an 87 m core from the southern Palmer Land plateau, representing the cyclonic regime of the west coast region, and a 133-m core from Dolleman Island, representing the more continental and colder regime of the Weddell Sea sector. In collaboration with the Geophysical Isotope Laboratory, University of Copenhagen, oxygen isotope data from these cores have been used to explore the detailed relationship between the isotopic composition and air temperature records from neighbouring weather stations (Figure 5). All the major regional temperature anomalies known from climatic records are visible in the isotope profiles, including a clear temperature increase of around 1.3°C between 1960 and 1980. This is approximately 4 times greater than the average change recorded elsewhere on the Antarctic continent.

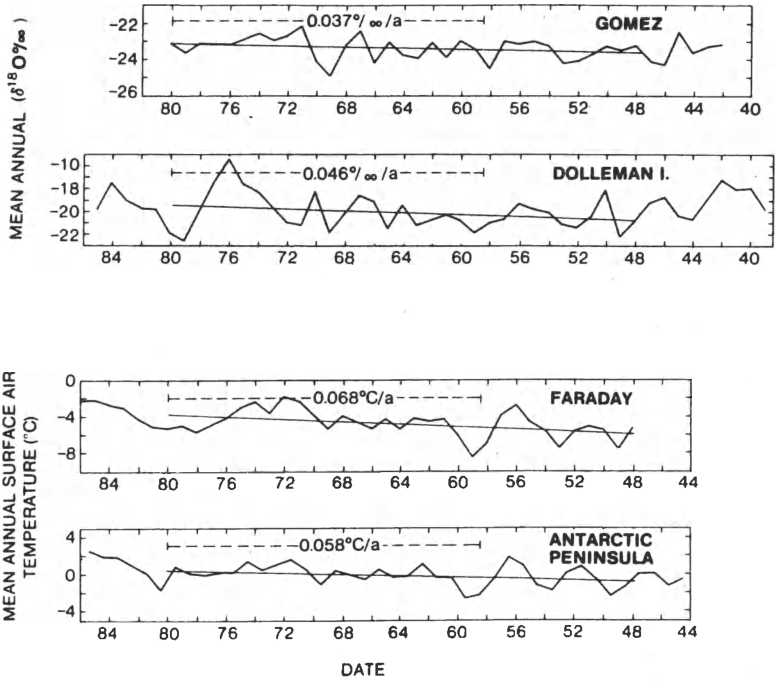

Fig. 5. Mean annual time-series of ^{18}O from Gomez and Dolleman ice cores in comparison with an instrumental record of air temperature from Faraday, and average record for the Antarctic Peninsula region.

Mainly due to the relatively large snow accumulation rate, the Antarctic Peninsula is one of the few areas of Antarctica where sites suitable for drilling yield cores in which climatic changes averaged over only a few years can be detected (Peel and others, 1987). The most notable trend during the past 30 years is an increase of more than 30% in the snow accumulation rate which has accompanied the overall temperature increase of 0.06°C a^{-1}.

In parallel with the isotopic studies detailed analysis of the major soluble inorganic ions is being carried out - including the anions chloride, sulphate (Figure 6) and nitrate (by ion chromatography), the cations sodium, potassium, calcium and magnesium (by atomic absorption spectometry and ion chromatography) and strong acid by low level acid titration (Mulvaney and Peel, 1987). The data are being used to develop new indices of climatic (e.g. cyclonic) activity and to evaluate factors closely related to climate including sea ice extent, volcanism and atmospheric turbidity.

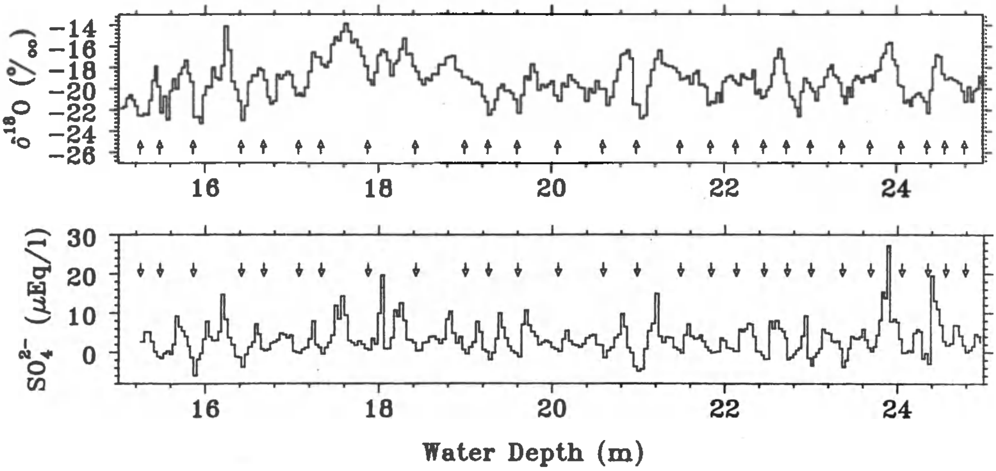

Fig. 6. Variations in sulphate and $\delta^{18}O$ in a section of the Dolleman Island ice core. Sulphate shows a clear seasonal cycle, with a maximum concentration during the austral summer.

Efforts have been made to devise new techniques for rapid and non-destructive dielectrical scanning of ice cores (Moore and Paren, 1987). These aim to identify at an early stage the most 'interesting' sections of the core for chemical analysis and could allow a core to be dated at the time of drilling. BAS glaciologists have designed and built an entirely new device for making continuous dielectric profiles along ice cores. Results confirm that the chemical content of ice is the main determinant of the electrical conductivity of ice at frequencies used for radio-echo sounding of glaciers (Moore, 1987). Thus the internal reflections seen in many radio-echo profiles are chemical in origin and can be used safely as isochrons in flow analysis.

In general the mechanisms of electrical conduction in polar ice have been poorly understood. Recently, however, BAS glaciologists have used scanning electron microscopy (SEM) to confirm a model they had proposed (Wolff and Paren, 1985) on theoretical grounds to account for DC conduction in ice. Using an X-ray microanalyzer fitted to the SEM, for the first time they showed (Mulvaney, Wolff and Oates, 1988) directly that sulphuric acid (but not sodium chloride) is localized at triple grain boundaries in an ice sample from the Antarctic Peninsula.

3.2.2 Global Pollution

Remote from industrial centres, or indeed from almost any kind of human activity, the Antarctic ice sheet has preserved a unique record of globally-dispersed air pollution (Wolff and Peel, 1985). A major advantage compared with studies elsewhere is that the human impact can be assessed directly by comparing the composition of recent snow with that of ancient ice. BAS has selected the heavy metals (lead, cadmium, zinc and copper) as a case study in view of their potential toxicity at low concentrations, and their widespread dispersal by industry.

BAS glaciologists spent several years developing suitable pre-concentration procedures and clean-room techniques (Landy, 1980; Wolff and others, 1981), now known to be essential for reliable work at the pg/g concentrations of heavy metals found in Antarctic ice. For lead, results for modern snow (Wolff and Peel, 1985; Dick and Peel, 1985) from the Antarctic Peninsula have helped to form a consensus on the present-day situation, between the few laboratories capable of making reliable measurements even in modern Antarctic snow. BAS measurements of Cd, Cu and Zn represent the only reliable values to date from Antarctica, showing order of magnitude reductions on previously-reported values.

Comparison of our data on modern snow with measurements that have been made on ancient ice, suggest that pollution may be responsible for up to 90% of the present lead content of Antarctic snow (Figure 7). However, there is now an urgent need to obtain detailed time series data covering the past few hundred years from both the Antarctic and Greenland ice sheets, at sites remote from any form of human activity. BAS scientists are currently analysing a series of ultra-clean snow blocks collected from a 9 m deep pit excavated in an area of very low snow accumulation rate in Coats Land, to evaluate trends through the last century.

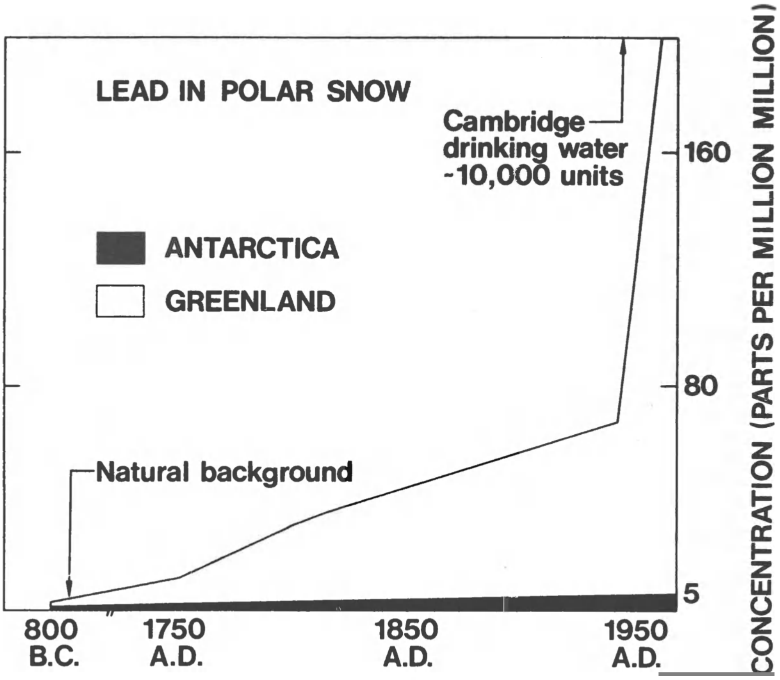

Fig 7. Contrasting trends of lead concentrations in Antarctic and Greenland snow arise mainly because 90% of pollutant emissions occur in the northern hemisphere and inter-hemispheric exchange of aerosols is limited.

In order to make a quantitative estimate of temporal changes in air pollution levels, and more generally of the composition of the atmospheric aerosol from ice-core data, it has been necessary to assume that these are uniformly related. BAS has made pioneering studies (Peel and Wolff, 1982; Dick and Peel, 1985) in the Antarctic Peninsula to explore this relationship directly by analysing aerosol and snowfall collected simultaneously at remote sites.

3.2.3 Future Plans

It is planned to conduct deeper drilling at several sites in Palmer Land in order to evaluate the inter-relationships between the dominant climatic zones and to develop further the link between palaeo climatic records from the interior of the ice sheet and those from lower latitudes. These studies will concentrate on the nature of high frequency climatic oscillation, such as those connected with the El-Nino-Southern oscillation, that are significant on the time scale of human activity. There will be a continued effort to develop empirical relationships between ice-core parameters and climatic signals and to explore the physical basis of these connections.

BAS will be keen to collaborate in larger international deep drilling activities in order to extend the time scale of its investigations and to develop a more complete understanding of the history of climatic and atmospheric processes over the West Antarctic Ice Sheet during the last glacial cycle. For example, parallel studies of cores from Berkner Island (as proposed by the European Science Foundation and the Antarctic Peninsula may help to link these latter records with the coastal strip of continental Antarctica. They should also help to resolve the role of the Weddell Sea in control of long-term climatic change over a major part of Western Antarctica.

ACKNOWLEDGEMENTS

I would like to thank Drs. C.S.M. Doake and D.A.Peel for their assistance in preparing material for this article.

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SCIENTIFIC RESEARCH ON THE ANTARCTIC IN FRANCE

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

ABSTRACT

France has no organism specialized in polar research. However, within laboratories depending on the "Centre National de la Recherche Scientifique" (CNRS), universities or other research organisms, some teams are dealing with specific problems about polar regions.

Three organisms coordinate on different accounts, the research efforts :

- The "Territoire des Terres Australes et Antarctiques Françaises" (TAAF), and especially its department "Mission de Recherche", chooses and finances the programs, upon advice of a Scientific Committee. Moreover, the TAAF takes charge of infrastructure and logistics. Its competence extends on Adélie Land (Antarctica) Kerguelen Islands, Crozet, Saint-Paul and Amsterdam (South of the Indian Ocean) as well as on "Marion-Dufresne", an oceanographic ship linking the various islands.
- The "Comité National Français de Recherche Antarctique" (CNFRA) corresponds to the SCAR. This organism introduces or co-ordinates international co-operation about antarctic or sub-antarctic research.
- The "Expéditions Polaires Françaises" (EPF) are in charge, on account of TAAF, of all operations in Adélie Land and of transportation to Antarctica. Their action covers the whole polar region, Arctic as well as Antarctic.

Foreign laboratories are entitled to participate in the various expeditions that the TAAF organizes, either on land or on the oceanographic ship. In the same way as the French projects, their requests are examined by the Scientific Committee. However, the TAAF does not finance the foreign projects.

Bilateral and multilateral co-operations are generally favoured. Consequently, some teams of Belgian biologists have been welcomed in Kerguelen and on board the "Marion-Dufresne".

To begin with, I should like to describe to you the structure within which scientific research on the Antarctic and sub-Antarctic regions is being developed in France. It is original in that it is not the sort of research conducted by specialist multidisciplinary institutes, as is the case in most member countries of the Antarctic Treaty, but involves researchers in existing laboratories who are interested in the polar regions providing them with logistical means and co-ordinating their efforts.

I shall then look at the main lines of research which are being followed at present and point out the trends in the immediate future with particular reference to the Antarctic.

In 1955, France, which owned three groups of islands in the Southern Indian Ocean – the Crozet Islands, the Kerguelen Islands and the islands of Saint-Paul and Amsterdam – and claimed Adélie Land in the Antarctic, created by law an autonomous Overseas Territory bringing together these four elements.

The French Southern and Antarctic Territories, the TAAF, have no population of their own and the main activity carried out there is scientific research. They are governed from Paris by a Higher Administrator assisted by a team of fifty people split up into three departments : sovereignty, logistics and research. It is this last-mentioned department which I run and to which I shall be devoting my attention above all. Its role is to implement all the research operations financed by the Territories and to supervise external operations.

Its sphere of competence is first of all the Territories proper, i.e. a purely Antarctic area with Adélie Land but also with the activities undertaken outiside Dumont d'Urville base, particularly in the field of glaciology, a sub-Antarctic area with Crozet and Kerguelen, both at a latitude of around 50° south, and finally an area which its latitude of 38° south could lead one to believe to be subtropical, that of Amsterdam Island and Saint-Paul, but which in fact has a climate similar to that of the Falklands and is frequented by typically sub-Antarctic seabird species.

Its second sphere of activity is in the ocean : the Marion-Dufresne, a relief vessel for the Southern Territories and also the largest French oceanographic vessel. It operates in the south of the Indian Ocean and in the Southern Ocean. It is not a polar vessel but is sufficiently reinforced to allow it to work within the polar circle when ice conditions permit. During the southern winter, it is used in tropical areas of the Indian Ocean and, exceptionally, the Atlantic Ocean. As regards the Polarbjorn, which is chartered in Norway to supply Dumont d'Urville and is a real polar vessel, its small capacity means that six return trips are necessary between Hobart and Adélie Land and it is therefore unable to take time off for oceanographic work.

Dumont d'Urville, in the Earstern Antarctic, is very isolated. Its closest neighbours are Casey 1,300 km to the west and Leningradskaïa 900 km to the east.

The coast of Adélie Land also has very little ice-free land, whilst the coastal region is an area of katabatic winds. At our old Port Martin base, for instance, the average wind speed is 40 knots, with the maximum exceeding 150 knots, and there are storms 220 days a year. It is therefore relatively difficult to set up there and the Pointe Géologie archipelago 10 km from the continent, where our current base is established, seems to be the only oasis in the region with a microclimate where numerous species can breed and man can work.

Crozet is the archipelago of birds, which find suitable nesting sites on its five islands and abundant food on the marine plateau surrounding them. The climate is harsher than on Kerguelen. Alfred Faure base on Possession Island houses some thirty people working on essentially biological programmes.

Kerguelen archipelago covers a wide area, 7,215 km^2, and has an infinite variety of landscapes. Its isolated position in the southern Indian Ocean, 3,600 km from any inhabitated land, Africa or Australia, has made it an indispensable platform for studying the Earth, either directly or via satellites. Its climate is extremely variable and is virtually always practicable. Its exploration, geological in particular, and the listing of its animal and vegetable populations are still incomplete. Port aux Français base is the largest in the Territories, with a population of 75 in winter rising to 130 or more in summer.

Amsterdam and Saint–Paul are two subactive volcanoes situated on the East Indian Ridge. Martin de Vivies, in the north of Amsterdam Island, houses a team of 30 people. Alongside biological and geophysical observation work, monitoring the pollution of the seabed is no doubt the most original activity on the island. The adjacent waters have substantial spiny lobster population exploited by the Territories, which make a not insignificant income from it and the stocks of which are strictly managed through my department.

The oceanographic equipment on board the Marion–Dufresne enables it to carry out all kinds of programmes. It has an oceanographic winch which, equipped with a kevlar cable, makes it possible to work with 25 tonnes per 7,000 metres of depth, allowing cores 50 m long by 117 mm in diameter or samples of 1 m^2 in section by 1 m deep to be taken without disturbing the sediment. The rear hydraulic gantry, with a capacity of 10 t, reaches down to water level. A fixed hydrology winch is equipped with a power–carrying cable. In addition to these fixed installations, numerous appliances on a 150 platform allow the vessel to be adapted for all types of purposes : fishing winches, trawling winches and seismic streamer winders, a boomer, hydrology winches, etc. The fixed installations also include containerized laboratories.

As I said at the beginning of this speech, the Territories do not have any scientific teams of their own. They are researchers from the "Centre National de la Recherche Scientifique" or Universities of the "Musée National d'Histoire Naturelle", or, less frequently, from the "Institut Français de recherche scientifique pour le développement en Coopération", better known as ORSTOM, or the "Institut National de Recherche Agronomique", and possibly foreign bodies proposing programmes in the Territories.

Before being implemented, these projects must pass through a number of evaluation stages.

First of all, the Research Department determines :

- the logistical constraints and the equipment needed;
- the personnel concerned;
- the possiblility or neccessity of grouping together with other projects;
- the cost and the financing schedule.

All this is recorded on a data sheet attached to the request to be submitted to the Scientific Committee for evaluation.

This committee has twelve members, all top-ranking scientists appointed ex officio by a number of research bodies or as experts by the Ministry of Research. The only condition imposed on their appointment is that they must not conduct any personal research in the Territories. The committee examines each programme proposed and draws up a report on :

- the scientific interest of the proposal;
- the proposer's ability to implement and exploit it;
- the acceptability of the scope of the project from the point of view of the resources and costs involved.

It may request additional information and suggest groupings.

Once in possession of all these reports, the Research Department establishes an operational project for the next campaign in accordance with the transport capacities on the vessels and the reception capacities of the bases, and the credits granted to it. This plan of operation is discussed by the Scientific Committee, which may amend it before approving it.

As I have said, the requests from foreign researchers are examined according to the same procedure. However, additional factors are taken into account – two primarily :

- Is there co-operation with a French team ?
- For what proportion of the logistics and the financing is the foreign team responsible ?

Lengthy discussions have been held – for a long while now – on the value of grouping together research teams working in the Southern Territories or the Antarctic, whatever their disciplines, within a Polar Institute. In the first stage, the exchange of ideas which would result from this grouping would certainly be beneficial to the development of the methods and techniques used in research at high latitudes. On the other hand, there is a risk within each discipline of the specialists in the polar regions, cut off from their usual community, becoming isolated.

It is a fact that horizontal integration is not seen in a good light in France. It is easier to gather people together around a theme than around a tool. Such is the case, for example, with oceanography, where, despite the creation of a specialized institute, research remains fragmented into multiple units.

The Research Department therefore has a role of promoting Antarctic research, a role of co-ordination and guidance. In a concern for efficiency and optimum utilization of the logistical means available, it must give priority to groups of programmes and multidisciplinary operations and promote work within a framework of national, bilateral or multinational co-operation.

Guidance is necessary to avoid dispersion and to optimize the use of resources. It is provided through two processes. The Scientific Committee calls in a group of experts to form a think tank which draws up a medium-term policy report, typically for a period of ten years.

Every three years, alternating between Antarctic and sub-Antarctic, a one-week colloquium is organized to which are invited all the researchers who have been active in polar regions, or would like to be, or who are simply interested in reporting on their work and setting out their plans, moving away a little from the original guidelines if necessary. The latest of these was held in Strasbourg in September 1987. The previous one, devoted to the Antarctic, took place in Grenoble in 1984, and I have given the secretariat some copies of the notes taken on this colloquium, together with some copies of the medium-term guidelines.

With a view to summing up these lines of research without going into too much detail and drowning you in exhaustive information, I shall try to give you a synthesis illustrated by a few slides.

First theme : the observatories.

The geographical isolation of the islands of the Indian Ocean and of Adélie Land is such that it is essential to maintain systematic observation of physical or biological parameters even if there is no possibility of immediate scientific exploitation. The acquisition of a series of quality data over long periods is one of the most precious commodities that we can and must provide as a contribution towards our understanding of the universe.

Consequently, in each of our bases we have observatories recording meteorological, magnetic and seismological data and monitoring populations of seabirds and marine mammals in the form of reference colonies, studies on the ionosphere and cosmic radiation on Kerguelen and in Adélie Land, and the auroras in Adélie Land.

The second theme concerns the inventory. Exploration of our area is far from complete. For the islands in particular, not all the colonies of seabirds or marine mammals have been the subject of a census. The inventory also concerns terrestrial and marine flora and invertebrates, geology, cartography and bathymetry, gravimetry, etc.

These first two major themes are more obligations towards the world scientific community than purposeful choices. We have made these choices for a certain number of fields of activity to which we decided to give priority and which I shall now summarize :

Five themes in biology :

- Nutrient salts.
- Primary production, phytoplankton and trophic webs.
- Genetic differentiation and speciation.
- Physiological adaptation to environmental conditions.
- Evolution of populations introduced deliberately or not.
  Whilst the Salmonidea introduced on Kerguelen are closely followed and carefully monitored, this is not the case with the cattle on Amsterdam Island, with rats, mice, rabbits and cats more or less everywhere, and even with sheep, mouflon and above all reindeer, whose recent ill-considered introduction is difficult to control.

Four themes in atmospheric physics :

- Study of the minor components of the atmosphere and pollution : a monitoring station, for CO_2 in particular, has now been in operation for some ten years on Amsterdam Island.
- Closely linked with the preceding theme but not yet really started, a study of the middle atmosphere and troposphere-stratosphere exchanges in the Antarctic. To obtain the best results from this study, it must be possible to work inside the Antarctic continent; I shall come back to this point. Linked up with this, however, are the ozone measurements which have just been resumed at Dumont d'Urville.
- Study of the katabatic winds, a programme conducted in conjunction with two American universities.
- Finally, palaeoclimatology and oceanic palaeocirculation, which undeniably represent the field in which we have made most efforts and also achieved most results. The reputation of French glaciology with Claude Lorius is already established and so is that of the marine sedimentology teams at Gif-sur-Yvette.

As regards the physics of the upper atmosphere, which for a long time constituted the essential part of our research work, we have retained only one theme : the physicochemistry of the auroras.

Finally, we are coming under strong pressure from our astronomers and astrophysicists to open up the Antarctic to them, which they regard as an ideal observation site. Here too, we do not have the means to meet their request immediately.

There are also some themes relating directly to oceanography :

- geophysics and structural geology – history of the Indian Ocean;
- marine chemistry and especially carbon and sulphur cycles;
- circulation and tropical monsoons, which takes us away from the Antarctic but allows us to make use of the Marion-Dufresne on its route, during the southern winter.

In conclusion, I should like to expand a little on our Antarctic projects. The coast of Adélie Land, apart from six rocky outcrops, is an ice cliff some thirty metres high, the rim of the ice sheet which in this sector has a long steep slope and is therefore deeply crevassed. It is a region affected by katabatic winds which carve out large sastrugas on the surface over about 200 km. Crossing the coastal aera is therefore a long, difficult and dangerous process. Consequently, activities within the continent are currently limited to glaciology alone and to campaigns wich are always too short.

Of the rocky sectors, only two have a sufficient extension to allow a base to be set up. Port Martin in the east, our first installation abandoned after a fire, has not been reoccupied because the climate is particularly aggressive there. In the Pointe Géologie archipelago, on the other hand, where the present Dumont d'Urville base is situated, 10 km from the coast in a cove sheltered by the glacial tongue of the Astrolabe, the meteorological conditions are relatively favourable.

Seven species of birds, including a colony of emperor penguins, take advantage of these circumstances. But, partly due to lack of space, human activity is limited there and of the priority themes selected only the observatory activities and the physiological study of adaptation, particulary of the emperor penguins, are developing satisfactorily.

Despite its quality, as I have said, glaciological research suffers from the difficulties in gaining access to the continent and really survives only within the framework of co-operation with the Soviets or the Americans.

Coastal marine oceanography has been slowly starting up again over the last two years. This too is short of resources for complex reasons relating to the functioning of the base for many years, but this situation should be able to evolve fairly quickly.

On the other hand, in so far as research into the physics of the middle and upper atmosphere or astronomy is concerned, we still do not have an infrastructure which would enable this work to develop. We have therefore planned a far-reaching equipment programme based on the opening up of an airstrip in the Pointe Géologie archipelago.

This study was long and delicate. We had to make sure that it was indeed impossible to construct this airstrip on the continent. This seemed obvious for numerous reasons, but every hypothesis had to be carefully analysed before acknowledging that it led to a technological impasse.

Constructing it in the archipelago posed the problem of competition with the species nesting on the islands which would be involved in the project. We ensured that neither construction nor use of the strip would affect the rarest species. Techniques have been developed to protect the species present whilst the work is in progress or to carry out the work in winter when the birds have left the Antarctic coasts. It is planned to lay out new areas where the displaced species can find accessible spots with an equivalent surface. This whole aspect of protection of fauna is followed very closely by the researchers at the "Centre d'Etude biologique des Animaux sauvages" of the CNRS, which is the most competent laboratory in France to deal with this sort of problem.

The strip will therefore be laid on a causeway linking up five small islands. It will be a little over 1,100 m long and will be able to take Transalls or C130s from Hobart, a journey over sea of 2,700 km. The work should be resumed this year and be completed by the end of the 1990–1991 summer campaign. A light aircraft fitted with skis, of the twin-otter type, will be permanently based at Dumont d'Urville for easy access to the plateau.

The second part of our project is the construction of an overwintering base for about fifteen people at Dome C, about 1,000 km from the coast. The project is progressing well, but we shall have to bring in aircrafts to complete it.

In fact, part of the equipment will be airdropped or parachuted in, whilst the heaviest loads will be transported overland in convoys relying on fuel dumps also deposited by plane. Essentially, this structure will be intended for programmes on the physics of the atmosphere and the upper atmosphere and astronomy. It will also serve to back up the summer glaciology programmes and will no doubt be completed by some observatory instruments.

We also think that we shall soon be able to open it up to foreign researchers. The project has been planned with a capacity for 15 people in winter, a figure which can be doubled in summer, but thanks to its modular design this capacity can be easily extended.

This reorientation of French operational logistics will also be favourable to oceanographic research. Since personnel transport will be entirely by air, the vessel chartered to carry the heavy equipment to Adélie Land will have to make only one trip a year for logistical purposes.

Consequently, and this is the third aspect of our project, our polar vessel can be allocated to oceanographic programmes working close to the continent in areas where ice prevents the Marion–Dufresne from gaining access.

The financing of these projects is well established and, without being over–optimistic, we can look forward to French research in the Antarctic making made a new leap forward within the next five years.

HIGH-RESOLUTION REFLECTION SEISMIC INVESTIGATIONS IN THE WEDDELL SEA DURING THE ANTARKTIS V/4 EXPEDITION

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

ABSTRACT

The ANTARKTIS V/4 expedition organized by the "Alfred-Wegener-Institut für Polar- und Meeresforschung" from December 1986 to March 1987 in the south-eastern Weddell Sea covered a broad spectrum of scientific programmes, ranging from glaciological land investigations to oceanographic and marine geological and geophysical surveys. In addition, the R.V. "Polarstern" provided logistic support to the permanent "Georg-von-Neumayer" base.

Due to exceptionally unfavourable ice conditions in the southern Weddell Sea, the initially planned Filchner shelf ice programme had to be cancelled. Instead, an integrated glaciological, geodetic and geophysical survey was carried out on the Ekstrom ice shelf, which should yield a better insight in the dynamics and the mass balance of this ice basin.

Once that the glaciological land programme had started, emphasis could be laid on the parallel execution of the main part of the marine survey.

The problem of cold bottom water formation in the Weddell Sea was addressed by CTD-profiling and current measurements with moored current meter arrays, sometimes implemented with sediment traps. The Weddell Sea dynamics were further analysed by tracer investigations.

Information on the recent environmental and climatic history of the Weddell Sea was acquired by sampling the shallow sea bottom sediments with box-corer and gravity corer. Early diagenesis of organic material was investigated by on the spot analyses of the sediment pore fluids. Sampling spots were carefully selected by preliminary site surveys with a 3.5 kHz subbottom profiler and a detailed three-dimensional mapping of the sea bottom morphology with the SEABEAM system of "Polarstern".

The deeper structure and stratigraphy of the continental margin of the eastern Weddell Sea was probed by high-resolution reflection seismic profiling, achieving penetration depths down to a couple of thousand metres below sea bottom. Parallelly recorded magnetic profiles should yield more information about the nature and structure of the underlying crustal material. In addition, deep refraction work with ocean bottom seismographs was carried out for analysing the seismic velocity structure of the continental shelf.

Throughout this multidisciplinary programme, due attention was paid to the stimulation of communication between the various pools of scientists through regular briefings, seminars and informal lab visits.

II. SCIENTIFIC PAPERS

HIGH-RESOLUTION REFLECTION SEISMIC INVESTIGATIONS IN THE WEDDELL SEA DURING THE ANTARKTIS V/4 EXPEDITION : SEISMIC RESULTS

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

SEISMIC INVESTIGATIONS IN THE WEDDELL SEA

KEYWORDS

Continental margin, High-resolution reflection seismics, Sedimentary sequences, Fine-scale stratigraphy, Ocean Drilling Program.

ABSTRACT

High-resolution seismic investigations have been carried out jointly by the Alfred-Wegener-Institut für Polar- und Meeresforschung (Bremerhaven) and the Renard Centre of Marine Geology (State University of Ghent, Belgium) in the Weddell Sea basin during the austral summer season 1986-1987. A total of 2869 km of seismic profiles, most of them with 24-channel data acquisition, have been shot in surveys which addressed four distinct marine geological domains :

(a) oblique prograding sediment wedges in the southern Weddell Sea, off Filchner Ice Shelf and Halley Bay ;

(b) a thick sedimentary sequence which possibly represents the distal part of a very extensive sedimentary fan, overlying the axial zone of a failed rift/drift basin ;

(c) the continental margin off Riiser-Larsen Ice Shelf and Cape Norvegia, close to the Explora Escarpment and the Wegener Canyon, where seismic support was provided to the ongoing drilling activities in the framework of Leg 113 of the Ocean Drilling Program ;

(d) the active plate boundary between Bransfield Strait and the South Orkneys, where a back-arc extensional basin is found in close association with an oblique subduction zone.

The high resolution which could be combined with a penetration down to a couple of thousand metres even in the deep-sea environment offered a unique opportunity to investigate different styles of sedimentary structures and sediment-tectonic deformation. Furthermore, the calibration of the seismic lines with the ODP drilling results will allow to define the stratigraphic context of the continental margin of the eastern Weddell Sea, possibly also leading to a correlation with the conjugate margins of austral Africa.

INTRODUCTION

Seismic investigations have been jointly carried out by the Alfred-Wegener-Institut für Polar- und Meeresforschung (Bremerhaven) and the Renard Centre of Marine Geology (State University of Ghent, Belgium) in the eastern and southeastern Weddell Sea basin and near the South Orkney Islands. This survey was carried out on board of the R.V. "Polarstern" during the austral summer period 1986-1987. A track plot is shown on Figure 1. A total of 2869 km of reflection seismic profiles have been shot, addressing four distinct marine geological domains :

- obliquely prograding sediment wedges in the southern Weddell Sea, in front of Halley Bay,
- a thick sedimentary sequence which possibly represents the distal part of a very extensive sedimentary fan, overlying the axial zone of a failed rift/drift basin,
- the continental margin off Riiser-Larsen Ice Shelf and Cape Norvegia, close to the Explora Escarpment and Wegener Canyon,
- the active plate boundary between Bransfield Strait and the South Orkney Islands.

The geological setting of the first three domains is illustrated on Figure 2 : the thick, obliquely prograding sequence is seen in the foreground, while the Cape Norvegia sector with the prominent Explora Escarpment is shown in the background.

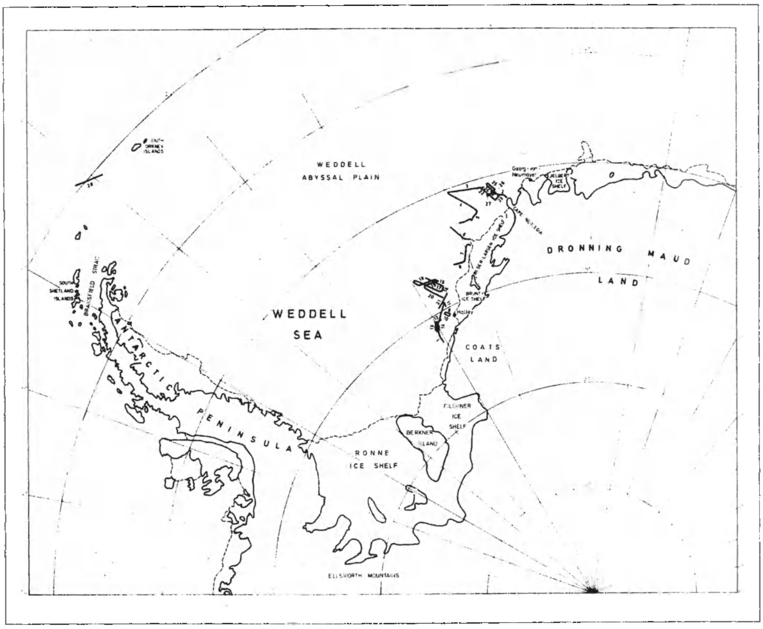


Figure 1. Seismic track plot, ANTARKTIS V/4 cruise

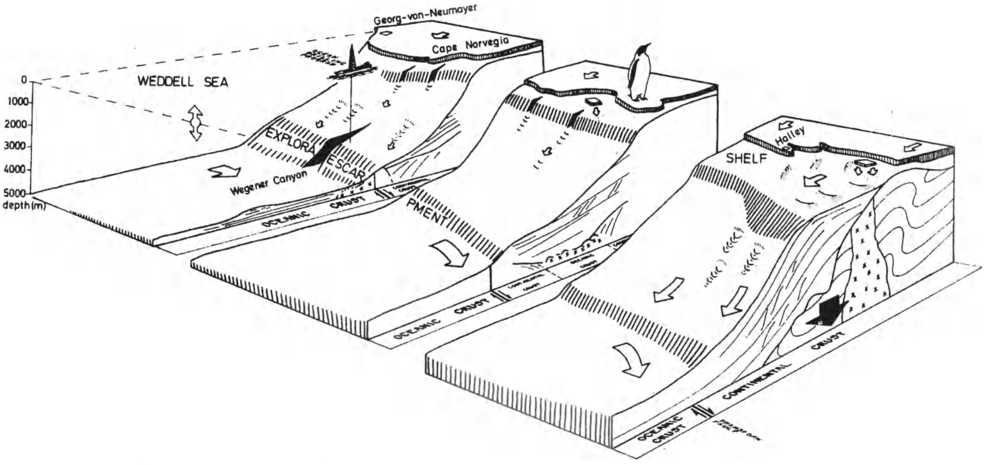


Figure 2. Schematic block diagram of the eastern Weddell Sea margin

MATERIALS AND METHODS

Four different marine seismic investigation methods have been applied during the ANTARKTIS V/4 cruise (Figure 3).

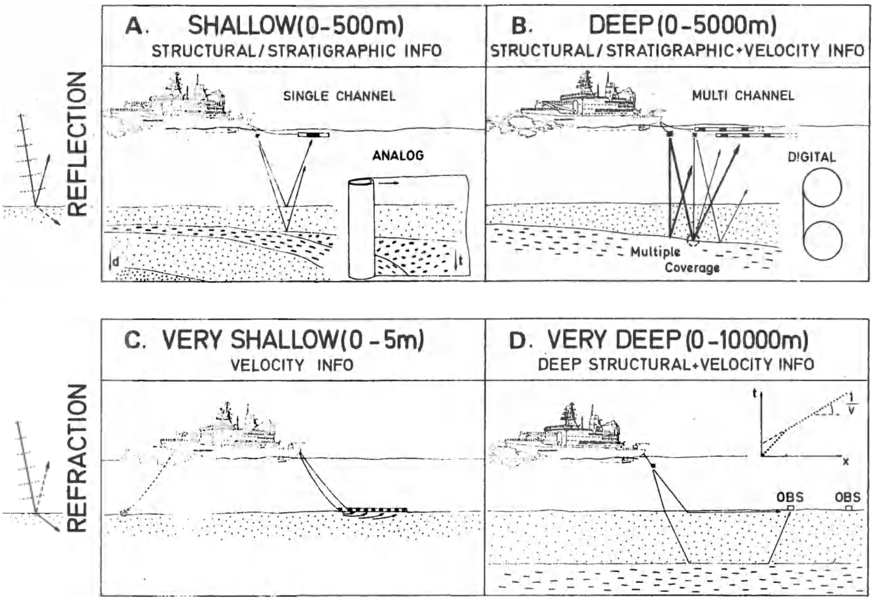


Figure 3. Marine seismic methods applied during the ANTARKTIS V/4 cruise

- High-resolution reflection seismic profiling with a penetration of 1000 m or more (Figure 3B)

A total of twenty-one profiles were shot with a penetration of some kilometres, still preserving a remarkably high resolution by adequate source array phasing and streamer depth control. The source array consisted of two or three PRAKLA-SEISMOS airguns with volumes of 0.5, 2.5 or 5 l, powered by compressed air at 14 MPa. Up to 6 compressors were available. Reflections were detected using a PRAKLA-SEISMOS streamer with an active length of 600 m and 96 hydrophone groups, clustered into a 24-

channel configuration. Digital data acquisition was performed on a EG & G GEOMETRICS ES-2420 seismograph, with data storage on two CIPHER tape drives. Parallel analog monitoring was provided on two EPC electrostatic paper recorders.

- High-resolution reflection seismic profiling of the shallow marine subsoil (Figure 3A)

Seven profiles were recorded in some of the shallower shelf areas, often close to the sea ice edge. One SODERA S15 watergun or a 12-electrode sparker fired at 4.5 kJ were used as seismic source, while detection of the reflections was performed with short 8-channel streamers (TELEDYNE) with active lengths of 50 or 100 m. Typical penetration values ranged from 200 to 500 m below sea-bottom. The data registration routine followed for this shallow acquisition was similar to the procedure described for the 24-channel data acquisition.

- Refraction seismic evaluation of the seismic velocity distribution in the surficial sea-bottom sediments (Figure 3C)

The main objective of this approach was to investigate the hard-bottom problem frequently encountered on shallow Antarctic continental margins. For this purpose a 16-channel refraction streamer with an active length of 32 m was lowered on the sea floor, jointly with a single-electrode sparker. Sediment samples were taken from the same sites with a gravity or piston corer.

- Deep crustal refraction sounding (Figure 3D)

The seismic structure of the upper few kilometres of the lithosphere under the eastern margin of the Weddell Sea was investigated with a 30 km long refraction profile, using the full airgun array capacity and two Ocean Bottom Seismographs of Hamburg University. Data processing will be carried out by AWI.

RESULTS

The preliminary interpretation of the analog reflection records already yields a qualitatively sound insight in the geological structure of the investigated areas. Further refinements of these interpretations may be expected from the analysis of the digitally processed data, which should become available in the forthcoming one or two years. Some highlights of the seismic results from the marine geological domains investigated are discussed below.

- The obliquely prograding sediment wedges off Halley Bay

The Cenozoic sequence in the southern Weddell Sea reaches a thickness of more than 5 km in front of Filchner Ice Shelf (Haugland, 1982). A characteristic feature is the presence of northerly and westerly prograding sedimentary units, capped by a continuous, semi-transparent cover. The obliquely prograding sequence gives evidence for a considerable sediment supply in earlier Cenozoic times, possibly in deltaic environments. As to the cover, its seismic facies suggests a glacigenic character. A few examples of profiles showing the upper part of obliquely prograding units are shown on Figure 4. Erosional scouring can be observed at various stratigraphic levels.

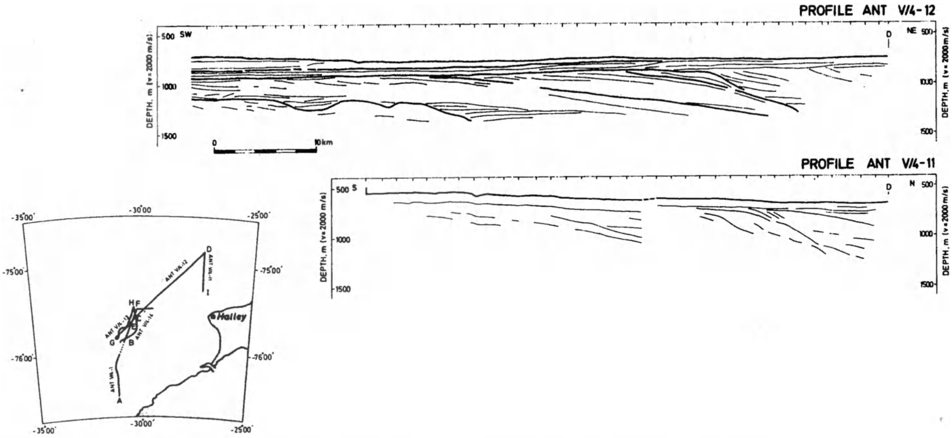


Figure 4. Profiles ANT V/4-11 and -12

- The sedimentary cover of the axial part of the failed rift/drift basin

A failed rift/drift basin was identified by Hinz (1987) in the eastern Weddell Sea. This basin is obliquely transsected by a major fault, marked in the sea-bed morphology by the Explora-Andenes Escarpment (Hinz and Krause, 1982 ; Haugland and Kristoffersen, 1985). According to Hinz (1987), the seismic facies of the axial zone of this basin suggests the presence of oceanic crustal material. This axial zone is flanked on either side by a conjugate set of diverging reflectors, dipping towards the oceanic axial zone : the so-called Explora Wedges (Hinz, 1981). Similar wedge-shaped units have already been cored in various DSDP or ODP Legs and proved to be of volcanic origin, associated with the initial break-up of continental crust in the earliest drifting phase (Hinz, 1981).
The southern extension of this basin has been investigated with a grid of 6 profiles, which did not confirm the nature of the deeper crustal material but instead yielded a detailed picture of the stratigraphy and sediment-tectonic features of the sedimentary cover, which locally reaches a thickness of some thousands of metres.
The basal series of this sedimentary sequence (Figure 5) consists of irregular, high-intensity, discontinuous reflections, dipping towards the centre of the Weddell Sea basin (A) and covered by an interval with weaker, subparallel reflections, which wedges out fairly rapidly in landward direction (B).
The overlying unit (C) is the most prominent one and consists of a sequence of strong, subparallel and continuous reflections, locally disturbed by basement-detached faulting and internal slumping (arrows, Figure 5). A remarkable observation is the occurrence of major stratigraphic gaps across some faults.
This sedimentary cover was recently interpreted by Kristoffersen et al. (1987) as the distal part of the extensive Crary Fan deposit.

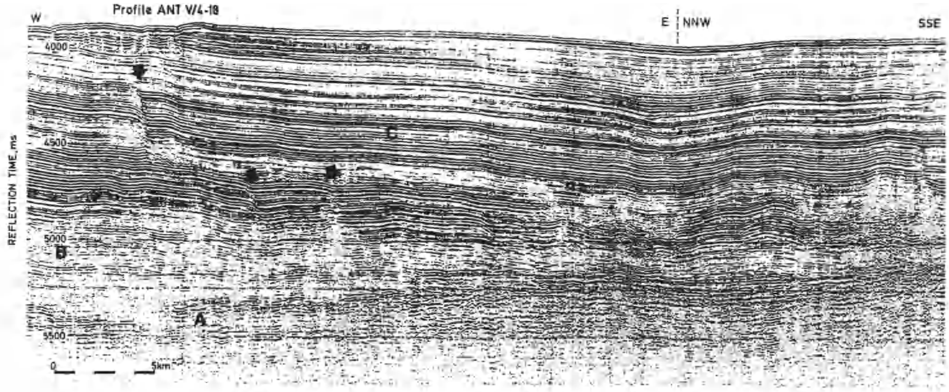


Figure 5. Profile ANT V/4-18

- The continental margin off Riiser-Larsen Ice Shelf and Cape Norvegia

The Explora-Andenes Escarpment takes a prominent morphological position in this area. It is locally deeply incised by erosional channels, such as the Wegener Canyon, which was mapped in detail with "Polarstern"'s SEABEAM system during the ANTARKTIS V/4 cruise (Figure 6).

In the framework of Leg 113 of the Ocean Drilling Program, two boreholes (50 and 465 m) were drilled from the drilling vessel "Joides Resolution" in a water depth of approximately 3100 m, one on either side of the upper part of Wegener Canyon. Shortly after the departure of "Joides Resolution", a grid of seismic profiles was shot by "Polarstern" over the drill sites, providing a tie line between both boreholes as well as three slope-to-basin profiles, one example of which is shown in Figure 6. The preliminary interpretation of the borehole data revealed a major hiatus between Cretaceous shales and Miocene glacigenic deposits.

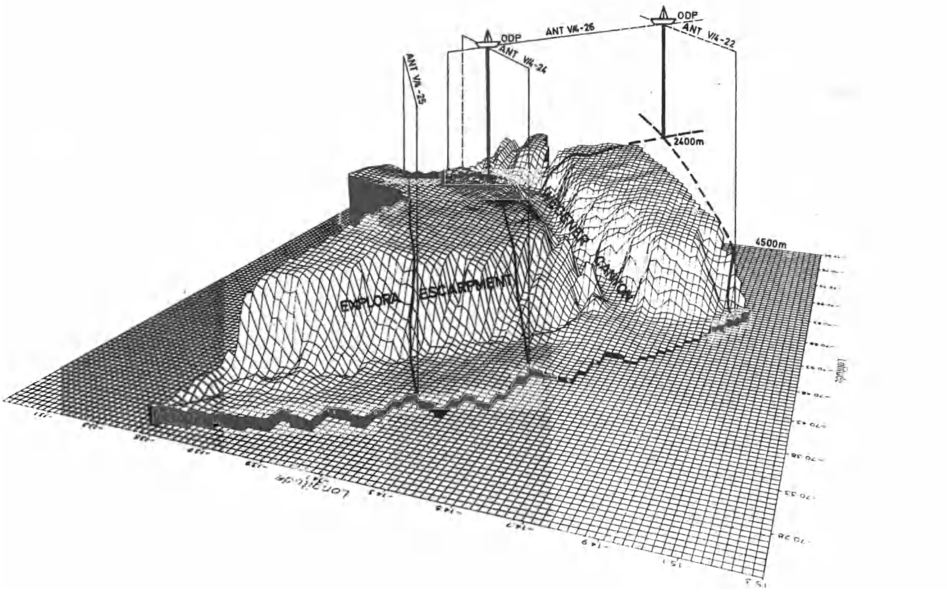


Figure 6. 3-D Presentation of the Wegener Canyon survey area (AWI SEABEAM plot)

Different depositional sequences could be identified within these glacigenic deposits on the seismic records. This observation, together with the observation of major cut and fill episodes in the deposits at the foot of the Explora Escarpment (Figure 7), might suggest a climatological signal, locked in these Neogene Antarctic continental margin deposits.

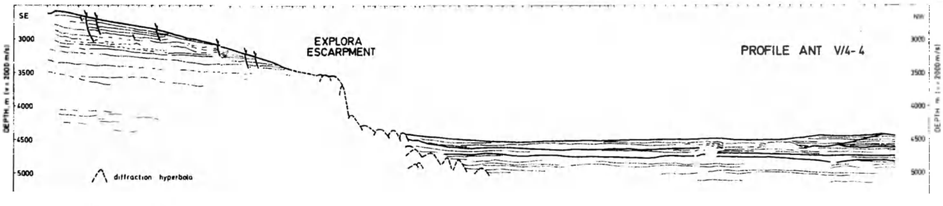
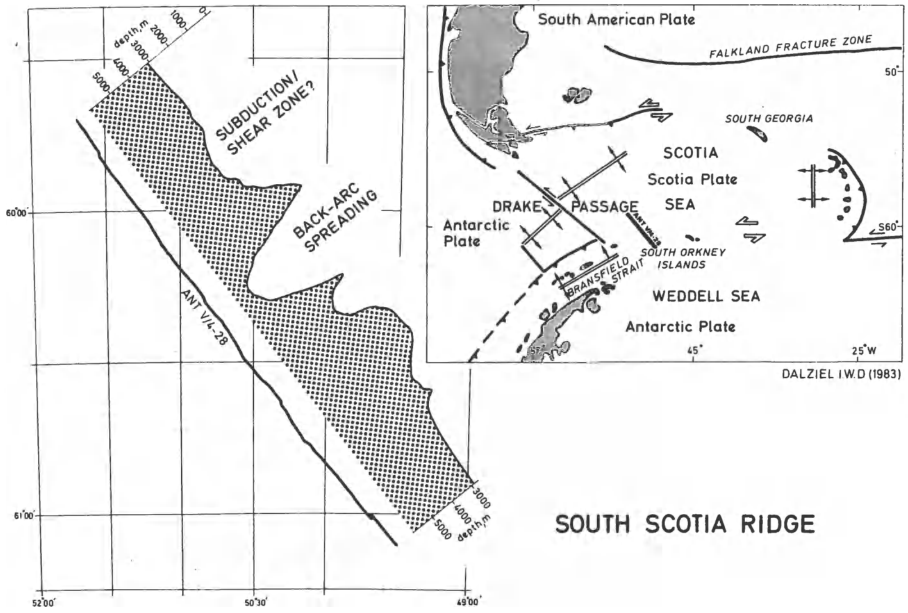


Figure 7. Profile ANT V/4-4

- The South Scotia Ridge area

One seismic profile was shot on "Polarstern"'s return route, between Bransfield Strait and the South Orkney Islands (Figure 8). This profile crossed a 5300 m deep trough with steep walls, which possibly marks the eastward prolongation of the extensional structure of Bransfield Strait. The bottom of this trough showed a conspicuous small ridge or mound, flanked on either side by very symmetrical diverging reflection sets.
Just beyond the ridge flanking this deep trough to the north, a bundle of faults affecting the whole sediment cover up to the sea floor forms the uppermost expression of a major active plate boundary, which in this region could be characterized by oblique subduction and shear movements.



DALZIEL I.W.D (1983)

SOUTH SCOTIA RIDGE

Figure 8. South Scotia Ridge

CONCLUSIONS

The very high quality and resolution which could be achieved in the reflection seismic investigations of the sedimentary wedges on the continental margin of the eastern and southeastern Weddell Sea sheds a new light on the fine-scale stratigraphy and on the basin dynamics of this region. Forthcoming detailed seismo-stratigraphic interpretations, implemented with the information from the ongoing analyses of the ODP cores, may yield a clue to the Cenozoic climatological record, locked in these deposits.

ACKNOWLEDGEMENTS

The present research was carried out by the Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI, Bremerhaven), in cooperation with the Renard Centre of Marine Geology (RCMG, Ghent University). This text presents research results of the Belgian Programme "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsibility is assumed by its authors. Support for RCMG's contribution to the ODP site study was also granted by the Belgian National Fund for Scientific Research. The Belgian authors wish to gratefully acknowledge the hospitality and stimulating spirit of cooperation enjoyed on board of R.V. "Polarstern".

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DISSOLVED BARIUM AND NUTRIENTS IN THE SOUTHERN OCEAN : THEIR POTENTIAL USE AS TRACERS FOR THE CHARACTERIZATION OF THE DIFFERENT WATERMASSES

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

KEY WORDS : barium, nutrients, watermasses, Southern Ocean.

ABSTRACT

The location of the main Southern Ocean frontal systems, identified from surface water data for salinity and temperature during INDIGO 3, determines the surface water values for nitrate, silica and barium. For nitrate the strongest gradient coincides with the Subtropical Convergence (STC; 42°S), with zero concentration north of this front and concentrations from 17 to 27 µmol/l south of it. North of the STC silica never is completely exhausted, while dissolved barium concentrations decrease to 40 nmol/l, the lowest values observed. Along the watercolumn within the Circumpolar Current the following watermasses are identified (from surface to bottom) : Antarctic Surface Water, Winter Water, Circumpolar Deep Water, Weddell Sea Deep Water and Antarctic Bottom Water.

Here, typical profiles for dissolved barium show surface values of 77 nmol/l and bottom values of 100 nmol/l. Along Antarctica some stations show a decrease in dissolved barium and silica in bottom waters. This indicates local bottom water formation, confirmed by freon-11 data for two stations in Wild Canyon (west of Amery Basin).

The maxima of particulate barium in the euphotic layer (-35m) and the oxygen minimum layer (-200m) suggest that both, active (the living phytoplankton cell) and passive (the desintegration of organic detritus microenvironments) processes control the production of barite.

1. INTRODUCTION.

From January 3thd to February 28th, 1987 we participated in the INDIGO 3 campaign, between 20°E and 85°E in the Southern Ocean (Figure 1). The main objective of our contribution was to gain more insight into the biogeochemical cycle of barium for which there exists a general interest due to the potential role of barium as a stable isotope for ^{226}Ra, a tracer of ocean circulation (see f.i. Chan et al., 1977; Broecker and Peng, 1982).

In this study we give special attention to the transfer process of barium from the dissolved to the particulate phase. Today, evidence exists that both, active and passive biological processes can be responsible for this phenomenon. Fresnel et al. (1979) and Gayral and Fresnel (1979) identified intravacuolar barite crystals in marine algae (Pavlovales). Numerous other observations indicate active production of barite as a rather common process, in both aquatic and terrestrial environments (see discussion in Dehairs et al.,1987). Active production of barite, however, is difficult to reconcile with the generally observed barite maxima occurring below the euphotic zone in the thermocline or oxygen minimum layer (Dehairs et al.,1980), unless heterotrophic organisms can control this production as suggested in Dehairs et al. (1987). The link between pelagic barite and the presence of organic microenvironments was first suggested by Chow and Goldberg (1960). Visual evidence (SEM-EMP techniques) of barite precipitation in such microenvironments was first given in Dehairs et al. (1980). Strong support for this latter process was given recently by Bishop (1987). Using SEM-EMP techniques, it is shown by Bishop that barite is formed within biogenic aggregates (fecal pellets, bio-aggregates, marine snow ...), usually containing empty frustules of Rhizosolenia diatoms.

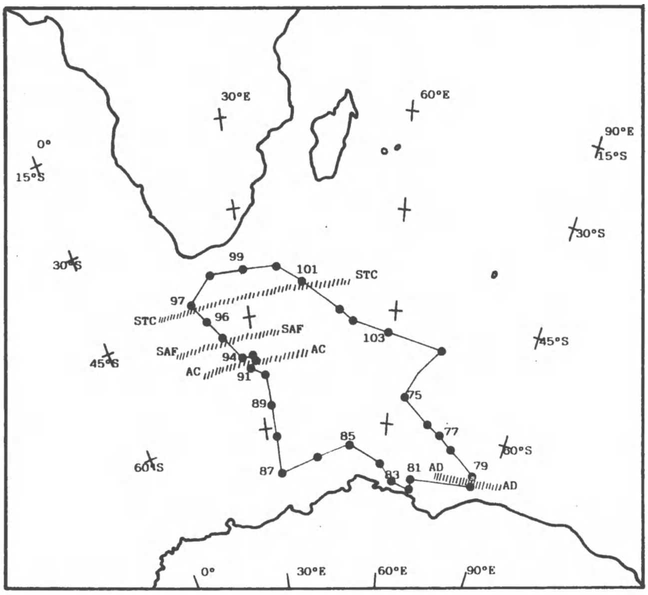


Figure 1 : Cruise track of the INDIGO 3 campaign.

One of our aims is to study the likely relationship between the intensity of organic matter remineralisation by heterotrophic bacteria and barite occurrence. As the Southern Ocean is characterized by increased plankton biomasses, associated with the main frontal systems (Lutjeharms et al., 1985; Hecq and Goffart, this issue), it offers an interesting opportunity to check the relationship(s) between increased plankton biomass and resulting bacterial activity on the one hand and barite occurrence on the other. Furthermore, the effect of an increased dissolved barium content in surface waters upon barite production can be studied. This increased barium concentration results from the upwelling of nutrient enriched deep waters along the Antarctic Divergence.

While these are our major objectives, participation in INDIGO 3 included also the routine determination of nitrate, nitrite, ammonia, dissolved Ba and particulate Ba, Ca, Sr and Al. From these data it became apparent that dissolved barium, as well as silica, carry a potential as tracers of local bottom water formation along Antarctica.

Not all analyses of barium and of the organic matter mineralisation experiments have as yet been completed. The discussion below, therefore, concerns only the distribution of the measured parameters and the preliminary conclusions to which they have led. This discussion includes the identification of the main frontal systems and watermasses present in the investigated area. The distribution of the nutrients (including barium) relative to these frontal systems, as well as the potential use of barium and silica as tracers of newly formed bottom water is discussed too.

2. EXPERIMENTAL.

In this work different parameters, measured by scientists of different laboratories, who participated to INDIGO 3 are discussed. Table I overviews these parameters, the analytical techniques used and the laboratories concerned.

Table I : Measured parameters

parameter	method	laboratory
hydrological parameters, temperature, salinity, pressure, dissolved oxygen	CTD, salinometer, Winkler titration	L.P.C.M. and L.O.DY.C., Univ. P. M. Curie, Paris
silica	Technicon Autoanalyser	L.P.C.H., La Mouette, C.N.E.S., Toulouse
nitrate	Technicon Autoanalyser	A.N.C.H., V.U.B., Brussels
dissolved barium	Resin extraction and GFAAS, (Dehairs et al., 1987); also direct determination by ICP	A.N.C.H., V.U.B., Brussels
particulate barium, calcium and strontium	$LiBO_2$ fusion and redissolution in HNO_3 (4%), ICP (according to Burman et al., 1978, and Schmitz, 1987)	A.N.C.H., V.U.B., Brussels

3. RESULTS AND DISCUSSION.

3.1. Main frontal systems and nutrient distributions.

Inspection of the continuous **temperature** profile in surface waters along the track between Antarctica and the African continent reveals the following temperature jumps associated with the different frontal sys- tems, in agreement with observations by Lutjeharms et al. (1985): (1) a temperature decrease from 20.4° to 13.5°C between 42°08'S and 39°54'S indicates the Subtropical Convergence (STC); (2) a temperature decrease from 9.3° to 5.4°C, between 46°24'S and 47°34'S indicates the Subantarctic Front (SAF); and (3) a temperature decrease from 6.8° to 3.6°C, between 48°54'S and 50°44'S indicates the Antarctic Convergence (AC), or Polar Front (Figure 2).

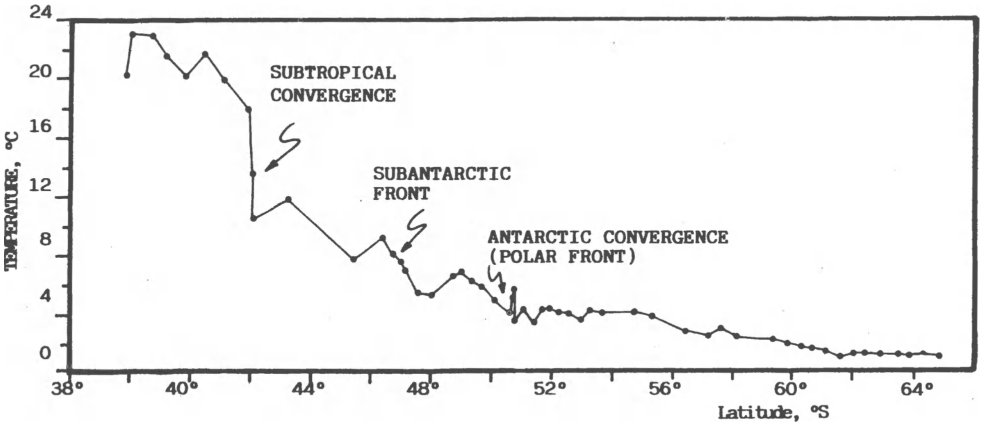


Figure 2 : Subsurface temperature distribution along the track between Antarctica and the African continent.

Furthermore, when inspecting the **salinity** data of surface water (-25 m) for the stations between 87 and 98 on the western track as well as for the stations 82 to 100 on the eastern track, it appears that an outcrop of high salinity water occurs at stations 80 and 81 (Figure 3). This outcrop of high salinity Circumpolar Deep Water (see below) is taken to indicate the location of the Antarctic Divergence (AD). It was not seen elsewhere along Antarctica during INDIGO 3. The position of these four frontal systems is indicated on Figure 1.

Surface water **nitrate** contents are highest south of station 89 in the west and 75 in the east, averaging 27 µmol/l (Figure 4). Stations 78, 79 and 80 in the easternmost corner of the cruise track show lower values, averaging 23 µmol/l, coinciding with higher Chl a contents (Hecq and Goffart, pers. comm.).

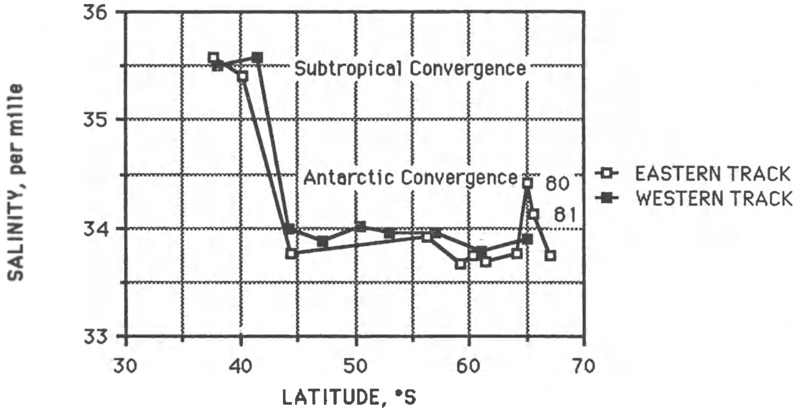


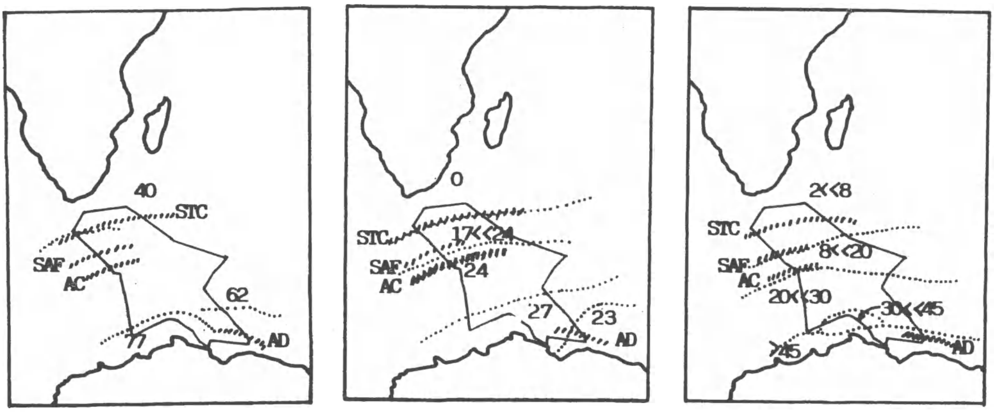
Figure 3 : Surface water salinities at INDIGO 3 stations.

From stations 88 to slightly north of the Polar Front (station 94) an average value of 24 µmol/l is observed. Then a first concentration decrease from 24 to 17 µmol/l occurs in the area between stations 96 and 97, crossed by the Subantarctic Front. The strongest nitrate gradient, from 17 µmol/l to complete depletion is observed between stations 96 and 97, when crossing the Subtropical Convergence.

The highest **silica** concentrations, exceeding 45µmol/l occur at some of the stations closest to Antarctica (79,80,81,82,83,84,87) (Figure 4). Stations 85 and 86 show values between 30 and 45 µmol/l. From stations 88 to 91 intermediate values, between 20 and 30 µmol/l were measured. Across the Polar Front concentrations decrease from 20 to 8 µmol/l. A further gradient from 8 to 2 µmol/l coincides with the Subantarctic Front. No complete depletion is observed for silica.

Not all profiles have as yet been measured for **dissolved barium**. Nevertheless, the available data allow to differentiate three zones (Figure 4). High concentrations, averaging 77 nmol/l (10.6 µg/l), are observed for the stations along Antarctica. To the north the concentrations decrease (62 nmol/l at station 76) to 40 nmol/l, the lowest value observed north of the Subtropical Convergence. This low concentration is similar to values found throughout the Atlantic between 40°N and 40°S (Chan <u>et</u>

al.,1977; Broecker and Peng, 1982) and respresents the Ba amount left after complete depletion of one of the limiting nutrients (nitrate in this case). This general observation was used by Broecker and Peng (1982) to catalogue barium as a biointermediate element.



barium **nitrate** **silica**

Figure 4 : Positions of the frontal systems, and distributions of dissolved barium (nmol/l), nitrate (μmol/l) and silica (μmol/l) in surface water.

3.2. Identification of watermasses present in the Circumpolar Current.

In Figure 5 the T_{pot}-salinity diagram is shown for stations 75, 76,78,79 in the eastern part of the cruise track. The general features of this diagram also appear for the stations along the track between Antarctica and Africa (not shown in Figure 5). From Figure 5 the following watermasses can be recognized (Jacobs et al.,1985; Poisson and Chen, 1987): **(1)** Antarctic Surface Water (AASW); salinity between 33.70 and 33.95 ‰; T_{pot} between +2.5° and +0.5°C. This water evolves from Circumpolar Deep Water (see below) upwelled along the Antarctic Divergence. **(2)** Winter Water (WW); salinity between 33.80 and 34.40 ‰; T_{pot} between -0.4° and -1.8°C. This temperature minimum is located in the halocline, at the basis of AASW and results from cooling of AASW to freezing temperature, during autumn and winter. Its higher salinity relative to AASW reflects salt rejection during freezing.

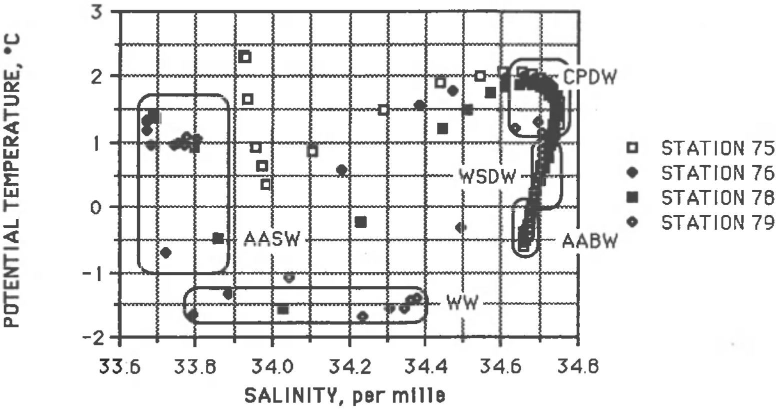


Figure 5 : Potential temperature - Salinity diagram for some stations in the Circumpolar Current.

(3) Circumpolar Deep Water (CPDW); salinity between 34.65 and 34.75 ‰; T_{pot} ~2°C. This watermass is fed by North Atlantic Deep Water (NADW). Towards the Antarctic Divergence it gradually shoals to outcrop eventually in the vicinity of the Divergence (see section 3.1 above). It is the only external water source near the continental shelf and as such all other watermasses must be derived from it. **(4)** Weddell Sea Deep Water (WSDW); salinity between 34.67 and 34.73 ‰; T_{pot} between +1° and -0.2°C. WSDW is slightly lower in temperature and salinity than CPDW. It originates from CPDW in the Weddell Sea where it circulates at intermediate depths within the Weddell gyre. **(5)** Antarctic Bottom Water (AABW); salinity between 34.65 and 34.67 ‰; T_{pot} between +0.2° and -0.5°C. AABW is also thought to be produced mainly in the Weddell Sea, as the result of mixing between WSDW, WW and Western Shelf Water.

In Figure 6 dissolved oxygen is plotted against salinity for the same stations as discussed above. An oxygen minimum layer with intermediate salinity values clearly differentiates from the salinity maximum associated with CPDW. This oxygen minimum results from processes endogenous to the Indian Ocean and Pacific Ocean sectors of the Circum- polar Current (Reid et al., 1977). It is not an extention of the oxygen minimum in the Atlantic Subequatorial, unlike the CPDW salinity maximum which is an extention of NADW. The strong oxygen increase in deep and bottom waters characterizes WSDW and AABW and allows to delineate their most northerly extent at ~45°S, between the surface water position of the Subantarctic and the Subtropical frontal systems.

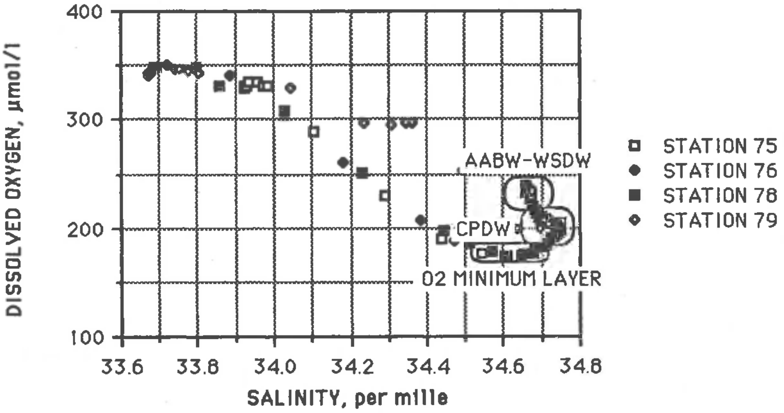


Figure 6 : Dissolved oxygen - Salinity diagram.

3.3. Dissolved barium and silica profiles along the Antarctic Continent. While for the majority of the stations, barium and silica concentrations increase gradually towards the ocean floor, some stations, all located in the transect along Antarctica, show a concentration decrease in deep and bottom waters (Figure 7). For that reason all barium and silica

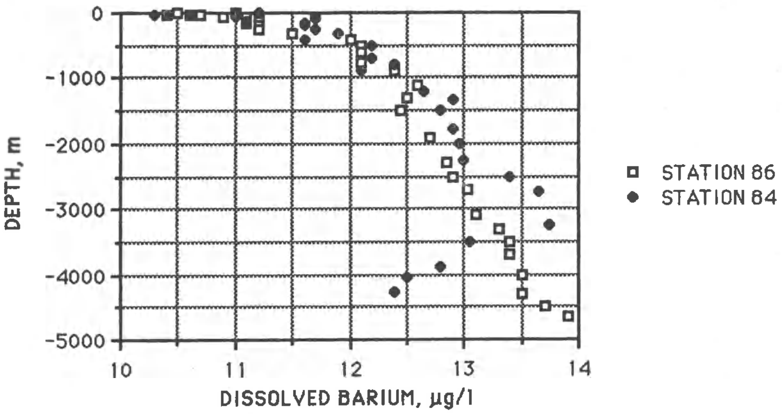
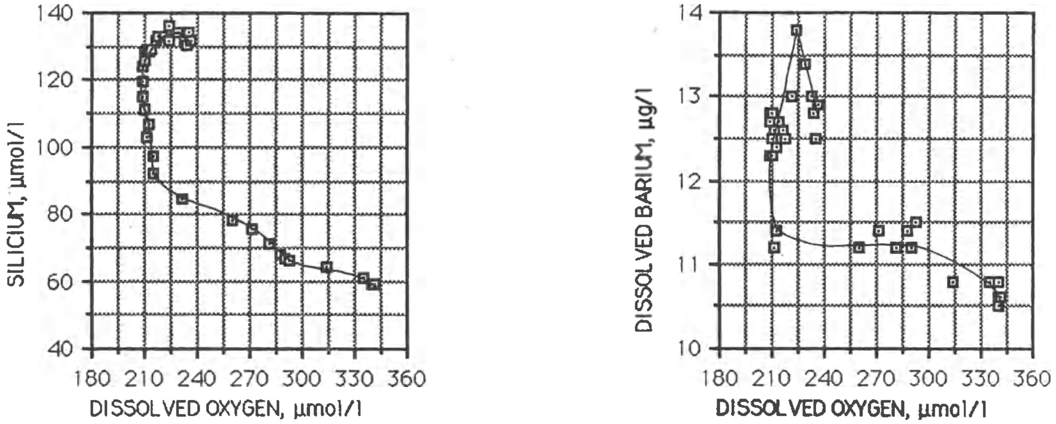
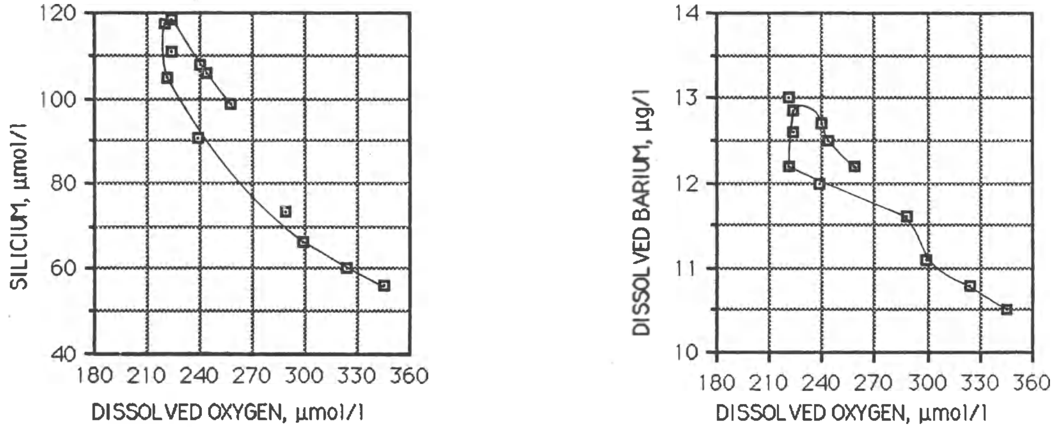


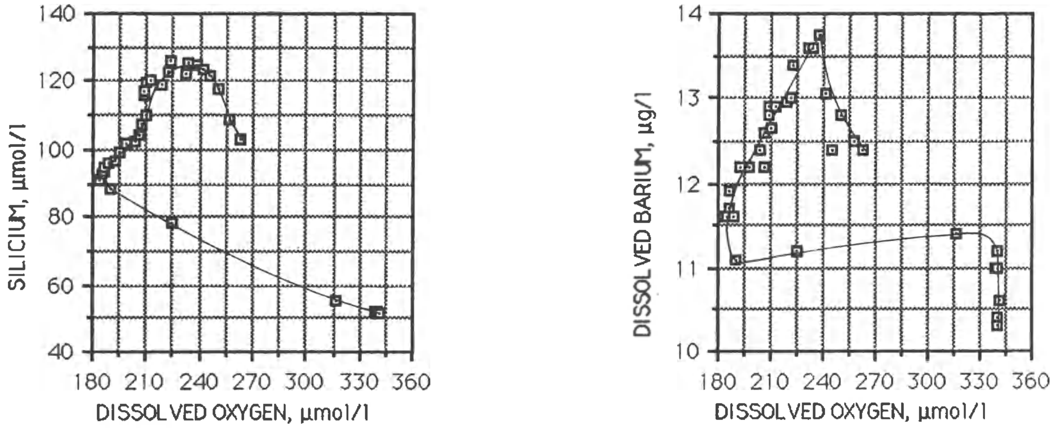
Figure 7 : Dissolved barium profiles at stations 84 and 86.



Station 81

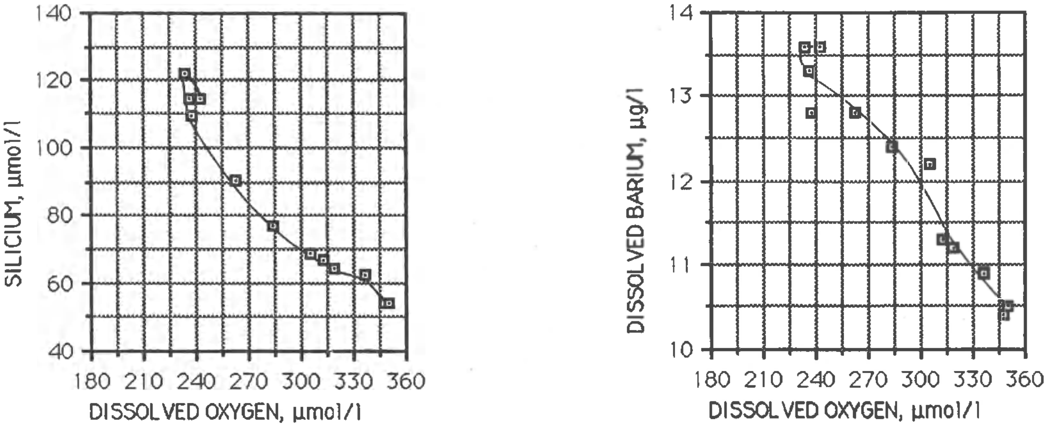


Station 82

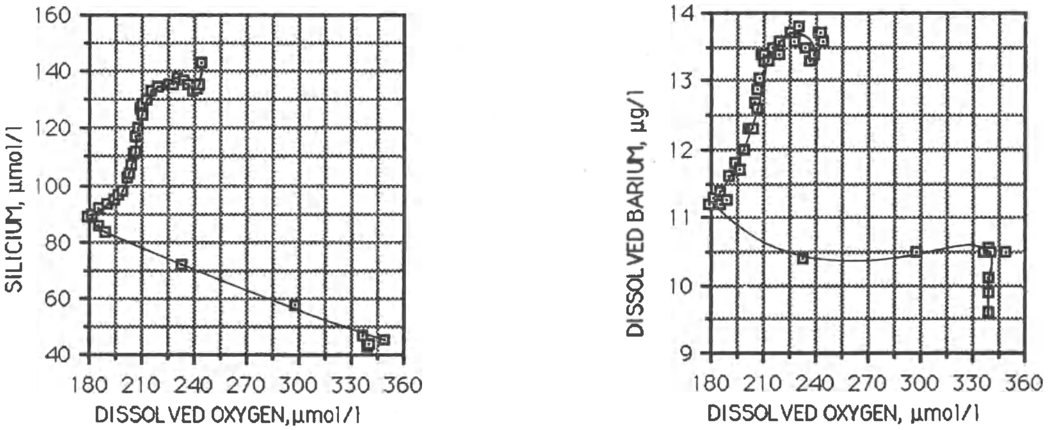


Station 84

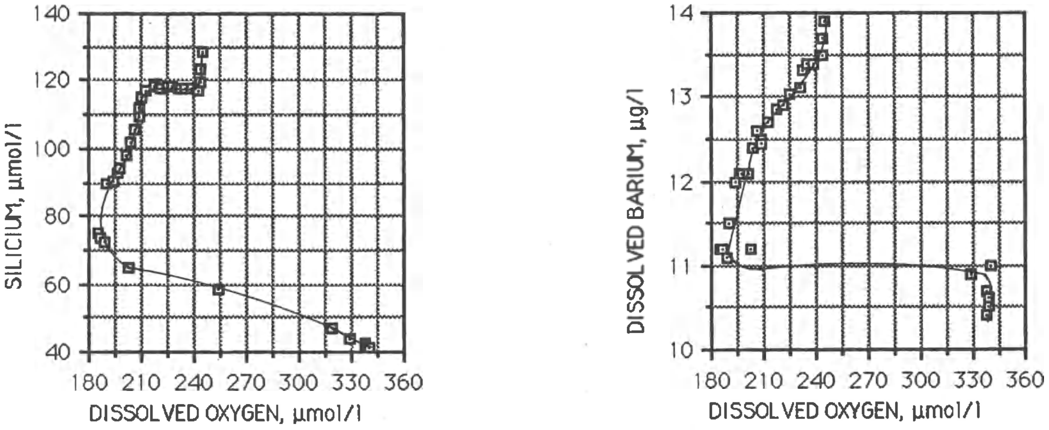
Figure 8A : Silicium - dissolved oxygen and dissolved barium - dissolved oxygen diagrams of stations 81, 82 and 84.



Station 83



Station 85



Station 86

Figure 8B : Silicium - dissolved oxygen and dissolved barium - dissolved oxygen diagrams of stations 83, 85 and 86.

profiles along the Antarctic continent were inspected. In Figure 8A and 8B these data are plotted against dissolved oxygen. Stations 81, 82 and 84 clearly show the barium and silica depletion in oxygen enriched deep and bottom waters. For station 83 this is not as clear, with only the sample closest to the sea floor showing a decrease. At station 85 the signal is less clear also, while for station 86 it is absent. Silica generally shows a similar behaviour as barium. Stations 87, 80 and 79, for which barium data are not yet available, do also show the silica depletion in bottom water. Focusing on the coastal and sea floor topography (Figure 9), stations 81 and 82 appear to be located along the Wild Canyon axis, just west of Amery Basin and Prydz Bay. For these two stations data on chlorofluorocarbons (freon-11) obtained by Mantisi (pers. comm.) show high values in surface waters, minimum values at intermediate depths and again higher values in bottom waters. This latter fact is clear evidence for newly formed bottom water flowing along the slope of Wild Canyon (Mantisi and Poisson, pers. comm.).

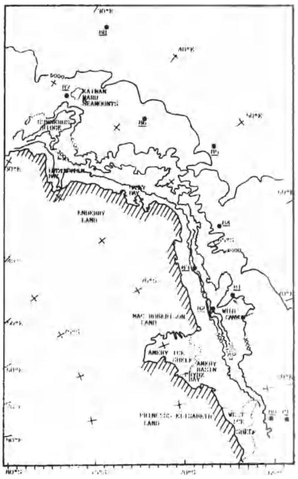


Figure 9 : Importance of the bottom topography near the Antarctic continent (from GEBCO CHART 5.18).

This observation further suggests the presence of newly formed bottom water at the other stations showing silica and barium depletions in deep and bottom waters. Inspection of Figures 8 and 9 then learns us that stations with newly formed bottom water are located on the continental slope (79,80,81,82) or close to it (84,87). Moreover, it is likely that bottom topography (81,82: Wild Canyon; 87: Gunnerus

Ridge and Kainan Maru seamounts) and ice shelf presence (79,80: West Ice Shelf) do influence bottom water formation and flow. It also is likely that the process of bottom water formation does not occur everywhere along the coast and does not occur with the same intensity. This is suggested by the data obtained for station 83 (Figure 8B) located on the slope close to the continent and showing only a weak signal, if at all, of newly formed bottom water. The possibility of bottom water formation was investigated earlier by Smith et al. (1984), who did not find evidence for it in Prydz Bay itself but who recognized this possibility for the region west of the bay off Enderby Land (Casey Bay?, Lutzow-Holm Bay?).

3.4. Particulate barium.

Up to now only one single station was analysed for particulate barium : station 86. The profile down to 1200 m is shown in Figure 10.

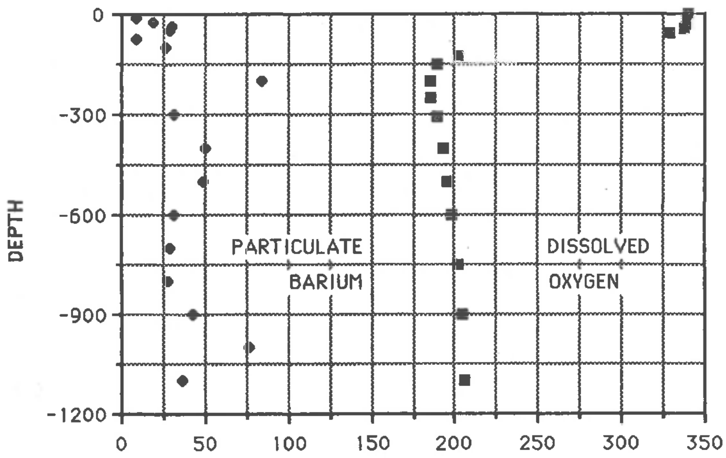


Figure 10 : Profiles of particulate barium (ng/l) and dissolved oxygen (µmol/l) of station 86.

Three distinct particulate barium maxima can be recognized: (1) at -35m, within the mixed layer and the euphotic zone. This maximum coincides with pronounced maxima of particulate Ca and Sr; (2) at -200m, coinciding with the oxygen minimum layer; (3) at -1000m, not correlated with any other parameter measured.

The -35m maximum is clearly associated with a plankton biomass maximum as evidenced by Sr and Ca. Chl a is uniformly high in this depth range (0.21 - 0.26 µg/l) with a single sample maximum of 0.41 µg/l at -78m (Hecq and Goffart, pers. comm.). The -200m maximum, related with the oxygen minimum, indicates the impact of heterotrophic consumption of detrital organic matter on barite release and possibly on barite production too. This is in agreement with the early hypothesis that barite is formed in microenvironments of decaying organic matter (Chow and Goldberg, 1960; Dehairs et al.,1980) and with recent observations of the occurrence of barite microcrystals within biogenic aggregates, containing empty frustules of the diatom Rhizosolenia (Bishop, 1987). Bishop states that barites are formed in surface waters within bioaggregates (> 53µm) and are released to the 1 - 53 µm size fraction below the surface by desintegration of the bioaggregate carrier. This release generally occurs in the depth range of the thermocline and/or the oxygen minimum (Dehairs et al.,1980; Bishop, 1987).

The possibility might exist that the particulate barium surface maximum at -35m, observed here, in fact represents barite in the large bioaggregates, described by Bishop. However, in view of the fact that we did use a sampling procedure (30 L Niskin bottles), that is different from the one used by Bishop (in situ large volume pumping and filtration), this seems rather improbable. Indeed, use of 30 L Niskin bottles disfavors the sampling of the large (> 53 µm) bioaggregates which can only be quantitatively sampled using large volume (several m^3) pumping and filtration devices. (Bishop et al., 1978; Bishop, 1987). Therefore, we favor the possibility that the very surface peak is in fact associated with certain species of **living** plankton and is thus likely to reflect **active** biological barite production.

The particulate barium maximum at -1000m is more difficult to explain. It requires a local input of barite. Settling of bioaggregates to -1000 m followed by desintegration and release of the individual barite crystals seems a plausible explanation.

4. CONCLUSIONS.

1. Surface water nutrient distributions, including barium, are clearly influenced by the frontal systems identified from temperature and salinity profilings.

2. Deep and bottom water depletions of dissolved barium and silica for certain stations in the vicinity of the Antarctic continent provide evidence for local formation of bottom water. For two stations occupied within a submarine canyon (Wild Canyon) this is confirmed by freon-11 data.

3. Evidence is provided that particulate barium may be controlled by two different biological processes, in agreement with earlier observations. One process is active biological production within the euphotic layer. The other process is passive

biological production within biogenic micro- environments followed by release of individual barite crystals, upon desintegration of the carrier by bacterial degradation. The latter release can occur within the oxygen minimum, but also at greater depths.

5. ACKNOWLEDGEMENTS.

We are grateful to the administration of the Terres Australes et Antarctiques Françaises for inviting us on board R.V. Marion Dufresne on this Southern Ocean campaign. We particularly thank Professor A. Poisson, (L.P.C.M., Université Pierre et Marie Curie, Paris), Chief Scientist of INDIGO 3, for integrating us into his research group and for his continuous assistance during the whole of the campaign. We are indebted to Dr. M. Hoenig (ISO, Tervuren) and to Dr. H. Neyberg (Geological Service, Ministry of Economic Affairs, Brussels) for granting us access, respectively to ET-AAS and ICP facilities and for assisting us during the analyses of dissolved barium. Dr. R. Van Der Linden and A. Dirickx (Mobil Polymers, Brussels) are thanked for assistance during ICP analyses of $LiBO_2$-fused suspended matter samples.

The following text presents research results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime MInister - Science Policy Office). The scientific responsibility is assumed by its authors. Frank Dehairs is Research Associate at the National Fund for Scientific Research, Belgium.

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PRELIMINARY DISCUSSION OF THE RESULTS OBTAINED IN ANTARCTICA DURING THE AUSTRAL SUMMER 1986-1987: PLANKTON ECOLOGY AND ECOTOXICOLOGY

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

Keywords:

Antarctica; bacterial biomass; PCBs; suspended particulate matter.

Abstract.

Making use of the expertise acquired during more than one decade in the North Sea in the fields of general ecology (C cycling, ecological structure) and ecotoxicology (transfer- and accumulation mechanisms of stable pollutants), we started a comparable study of the Antarctic ecosystems. The aim of this study is to test the generality of the concepts developped for the North Sea systems, and to obtain information on Antarctica, where only fragmentary data are available.

1. Plankton ecology.

Three zones were recognized, when considering the amount of bacteria in the upper (mixed) layer of the water column: Antarctic water (mean concentration: 9 10^4 bacteria/ml), south of the Antarctic Divergence (17), and sub-tropical water closer to Africa (37). There exist however also differences in cell volume, so that the differences in biomass are less marked: 1.9, 3.7 and 4.0 µg C/l respectively. These values are clearly lower than in temperate zones.

The relationship between bacterial biomass and phytoplankton biomass (chlorophyll) however shows a ratio very similar to the one of the temperate zones, suggesting a similar role of planktonic bacteria in the recycling of primary production.

2. Plankton ecotoxicology.

From the first results of analysis of organochlorines in particulate matter (mainly phytoplankton), it appears that the concentrations of PCBs are high: 0.75 µg/g dry weight, of the same level as in temperate zones. In order to interprate such results correctly, it is however necessary to express them in other units like lipid weight and per volume of seawater. Per volume, the contamination seems more constant, a conclusion already obtained in the North Sea, but lower than in temperate zones. The explanation is that the Antarctic is less contaminated than our regions -as expected- but that the very low biomasses present cause high levels per unit of biomass.

1. PLANKTON ECOLOGY.

Introduction.

In the frame of a synecological study of the Antarctic ecosystems, our aim is to determine the activity of the basic levels of the planktonic foodchain: primary production and microheterotrophs.

The problems in Antarctica concern basically the ecological structure of the system (relative roles of zooplankton and of microheterotrophs in the recycling of primary products) and its consequences for the higher trophic levels: fish, seabirds and marine mammals. On the other hand, indirect information exists, indicating that the measured primary production could be to low for explaining the observed biomasses of the higher levels. This is why we are also concerned by the determination of the real, *in situ*, primary production.

A few preliminary results were gathered in this direction during the 1986/1987 cruise.

Material and methods.

At the different stations (see Fig 1), water was sampled at 14 depths: 11 in the upper layer (0-250 m), two in the intermediate layer (900-1000 m) and one in the bottom layer (about 25 m above the bottom). The samples were immediately fixed with formaldehyde (2 % final concentration) and stored. Later in the laboratory, bacteria were coloured with Acridine Orange, following the procedure recommended by Parsons *et al.* (1984) with slight modifications (stain for 5 minutes and put paraffin oil on the stained filter), and counted under a (Leitz Dialux) epifluorescence microscope equiped with a 1513418 filter.

A decrease of the bacterial number in function of storage time was described by Joiris and Ye Dezan (1988) for North Sea samples, with a decrease of about 20 % per month. In the case of Antarctic water, five samples were counted twice, at time intervals varying between 24 and 41 days: a mean decrease of 20.7 % per month was found. This is why all results were corrected for the time elapsed between fixation and count, using the equation established in more details for the North Sea.

The bacterial size was measured by projecting slides taken under microscope (as well as a 10 µm grid). The volume was calculated as $\pi/4\ W^2\ (L-W/3)$, L and W being the length and width of the cell. The biomass was than calculated with the conversion factor $1.2\ 10^{-13}$ g C/μm^3 (Fuhrman and Azam, 1980; Bratabak, 1985).

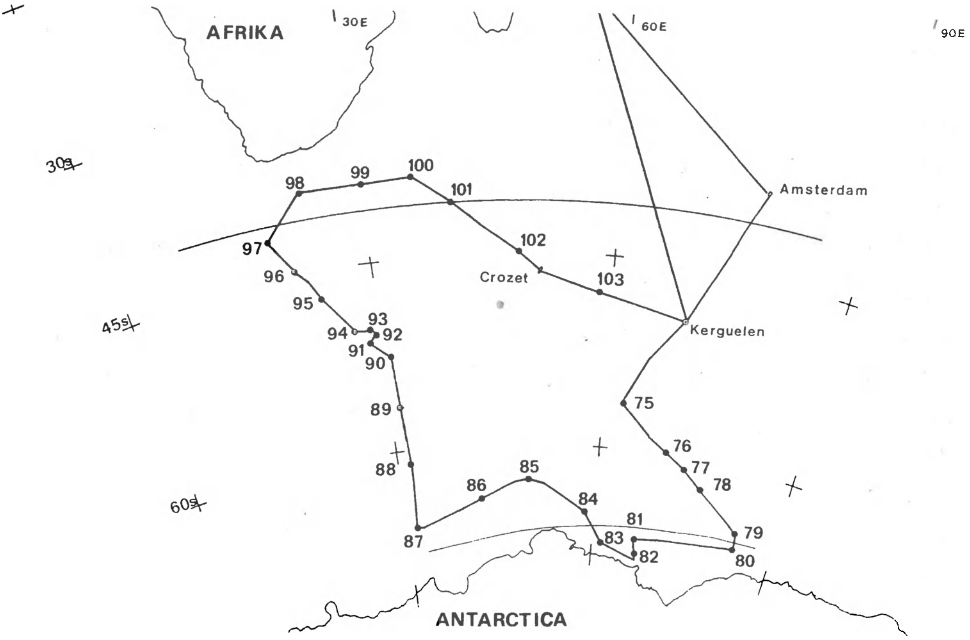

Figure 1: Localization of the sampling stations for bacteriology. The limit between zones is indicated by the thin lines (fronts).

Results and discussion.

The depth of the upper mixed layer was determined, using the vertical profiles of water density (data recorded on board RV Marion Dufresne by the team of Dr Poisson), at the maximum gradient of density.

The bacterial (direct) counts for the upper layer allow to recognize three main zones: (from South to North:) between the continent and the Antarctic Divergence ($17 \cdot 10^4$ bacteria /ml); between the Divergence and the Sub-tropical front ($9 \cdot 10^4$ bacteria /ml); and sub-tropical water closer to South Africa (37) (Fig 2). The existence of heterogeneities within the zones could be due to spatial variations, but temporal variations are not excluded, in connection f.i. with the evolution of the phytoplankton bloom because of the delay between the eastern and western legs.

There exists however a difference in mean cell volume for the three zones (table 1), so that the differences in biomass are less marked: 1.9, 3.7 and 4.0 µg C/l respectively (Fig 3)

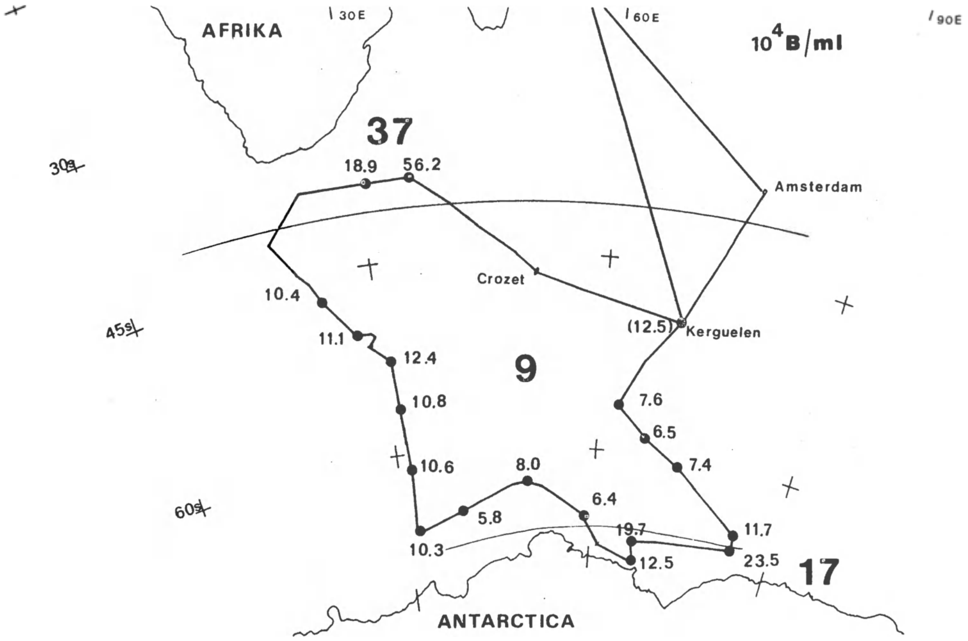

Figure 2: Bacterial (direct) counts in the upper layer (10^4 bacteria/ml, mean value); mean value per zone represented by big figures.

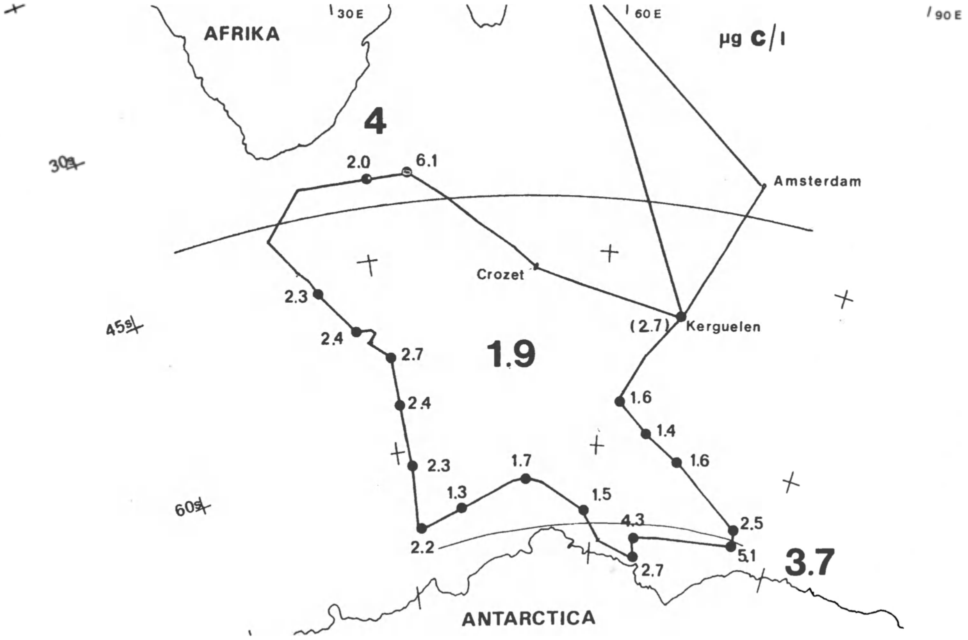

Figure 3: Bacterial biomass in the upper layer (µg C/l, mean value). See legend Fig. 2.

These values are much lower than in temperate zones: in the North Sea, by using exactly the same techniques, we obtained counts of 15 10^5 bact./ml in summer and 5.4 in winter, and biomasses of 73 and 26 µg C /l respectively (Joiris and Ye Dezan, 1988). Because of the wide range of both series of results, there exists however an overlap in counts and in volume between North Sea and Antarctica.

The distribution of bacterial counts and biomasses reflect a clear vertical structure, both parameters showing a strong diminuation under the picnocline and decreasing to values as low as $0.3 \cdot 10^4$ bact /ml and 0.1 µg C/l in the deeper layer (Fig 4). It must be noted that the most important part of the Antarctic water is occupied by low bacterial concentrations: this does not appear immediately on the figure because of the interruptions in the depth scale.

Table I: Summary of the data on bacterial number, volume and biomass in Antarctica (and in the North Sea for comparison). Zones within Antarctica: Antarctic water = 1; closer to the continent = 2; sub-tropical = 3. Zones within the North Sea: coastal = 1; offshore = 2. *(n)*: number of measurements.

Region (season)	Number (10^4 bact/ml)	Cell volume (µm^3)	Biomass (µg C /l)
Antarctic 1	9.1 *(10)*	0.151 *(25)*	1.9 *(10)*
Antarctic 2	17.0 *(7)*	0.192 *(67)*	3.7 *(7)*
Antarctic 3	37.0 *(10)*	0.090 *(34)*	4.1 *(10)*
North Sea 1	190.0 *(6)*	0.312 *(42)*	93 *(6)*
North Sea 2	98.6 *(5)*	0.430 *(164)*	48 *(5)*
(summer)			
North Sea 1	101.0 *(5)*	(idem)	49 *(5)*
North Sea 2	32.6 *(11)*	(idem)	16 *(11)*
(winter).			

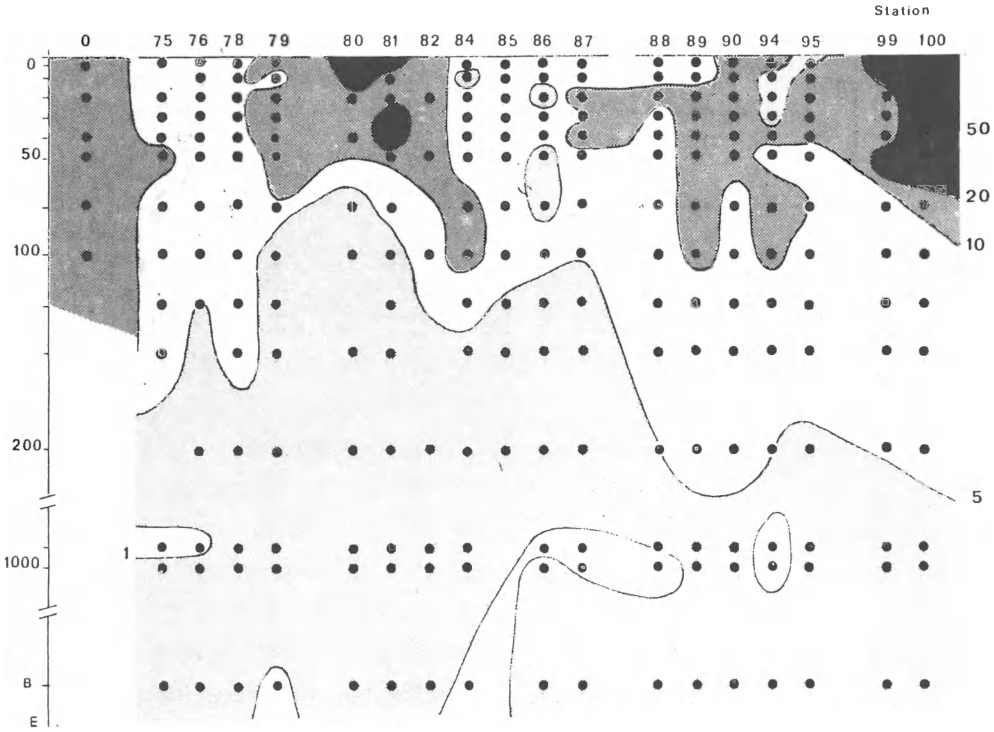

Figure 4: Vertical distribution of bacterial number (direct count) at the different stations (10^4 bacteria/ml). Note the interruptions in the depth scale

A first discussion on the relationship between primary production and recycling by planktonic bacteria can be done by establishing the chlorophyll to bacteria ratio (Fig. 5). The most obvious conclusion concerns the order of magnitude of this ratio, being comparable to the one found in temperate zones even if both parameters show much lower values. Since these coastal temperate ecosystems are characterized by an important bacterial recycling and very low zooplankton grazing (for the North Sea, see Joiris *et al.*, 1982), the results indicate that the Antarctic systems could have a similar ecological structure. This conclusion, if confirmed by other determinations, can deeply influence our view on the Antarctic ecosystems and our comprehension of the basic mechanisms determining the density of the higher level organisms: fish, seabirds and marine mammals.

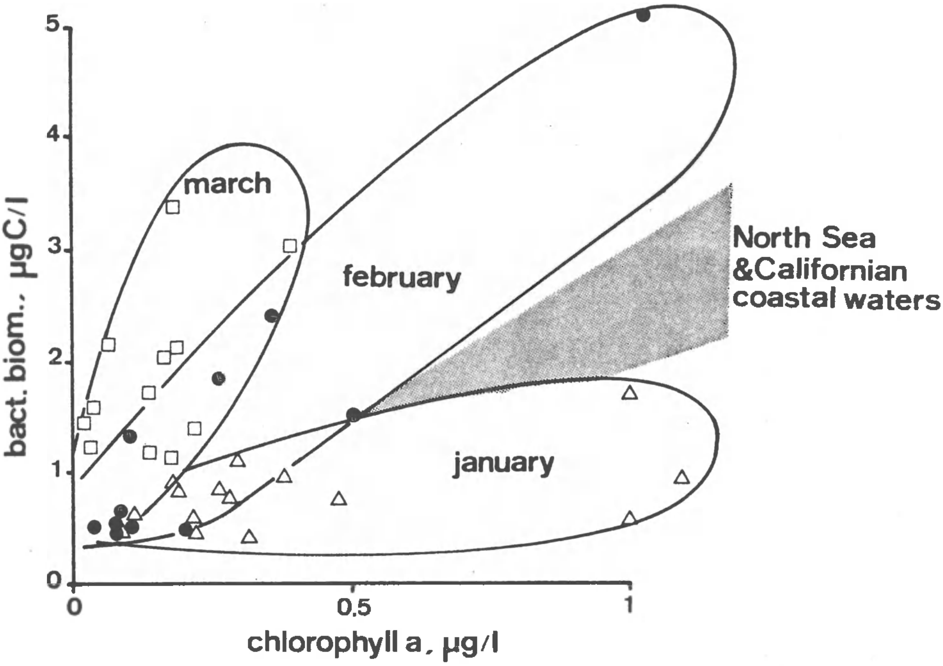

Figure 5: Relationship between phytoplankton biomass (chlorophyll a) and bacterial biomass in Antarctica. (Chlorophyll data: G. Billen and JH. Hecq; bacteria data: G. Billen and this study). See discussion in Billen *et al.*, these proceedings.

2. PLANKTON ECOTOXICOLOGY.

Introduction.

The approach in the study of stable pollutants such as PCBs, DDTs and heavy metals in the Antarctic environment is based upon our expertise acquired in the North Sea ecosystem. In order to describe and to understand pollution in marine ecosystems and so to be able to predict the evolution of the contamination, it is necessary to make a detailed study of transfer mechanisms of stable pollutants between the biological compartments. A lot of results have been gathered in the North Sea ecosystem on PCBs, DDTs and mercury transfer and accumulation mechanisms (Delbeke and Joiris,1985). The problem was studied in different steps:

- the contamination of the main compartments was determined: particulate matter (phytoplankton), zooplankton, fish, seabirds and sediments;
- the contamination of different periods and zones of the North Sea was compared on bases of wet weight, dry weight, fat weight and volume unit (m^3).

The main conclusions and concepts from this study were :

- the results obtained in the field have to be expressed and compared in different systems of units;
- the most important mechanism for particulate matter contamination seems to be adsorption/partition since the PCB levels of particulate matter remain constant per volume of seawater: PCBs are mainly bound to particles, very little remains in solution;
- the PCB level in zooplankton is comparable and even lower than in phytoplankton; together with the absence of a clear lipid-PCB relationship, these indications are in favour of PCB intake through the food and biological elimination as main mechanism;
- no important bioaccumulation is taking place at the level of fish. A strong lipid-PCB relationship points out to the importance of partition as regulation, although much controversy exists in the literature on fish data : argumentation is found aswell for direct (from the water) as for indirect (through the food) contamination. Additional laboratory experiments should clear this out;
- the most important bioaccumulation is taking place at the level of seabird: upto 40 times higher contamination than in fish;
- an important contribution to the question of direct or indirect contaminations will be a qualitative and quantitative determination of the lipids in the different compartments and their specific contamination;
- similar studies on mercury contamination show striking analogies with the organochlorines indicating the existence of similar mechanisms.

The aim of the study in Antarctica concerning bioaccumulation and transfer mechanisms of stable pollutants is to test the generality of the concepts described above in an environment characterized by various physico-chemical and hydrological conditions comparable to the North Sea systems (Bouquegneau and Joiris, 1987).

Besides this added scientific value to the problematic in the North Sea, the determination of the expected low concentrations in the Antarctic ocean, where only fragmentary data exist, is of utmost importance.

The contamination will be determined in two compartments: particulate matter and zooplankton.The lipid composition of these compartments will be analysed qualitatively and quantitatively.

Material and methods.

Sampling.

Particulate matter (mainly phytoplankton) was sampled during the INDIGO III cruise in the Indian sector of the Southern ocean by continuous centrifugation, and samples recolted about every 24 hours in order to obtain sufficient material to determine PCBs, DDTs and heavy metals. This resulted in 37 samples (Fig 6).

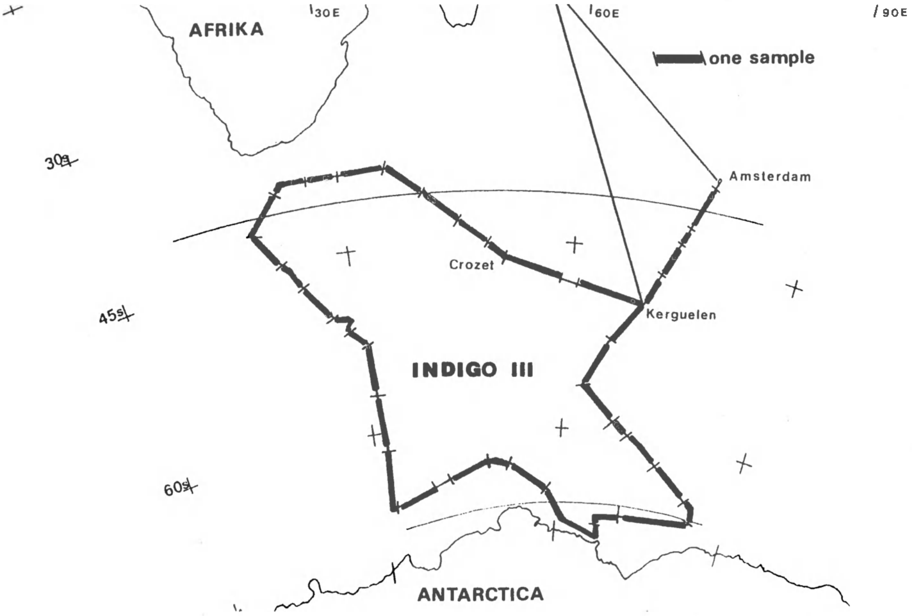

Figure 6: Localization of the sampling stations for particulate matter (continuous centrifugation).

Analysis.

Extraction and clean-up.

- 1 à 20 g. sample (wet weight) is homogenized after addition of water free Na_2SO_4: the material becomes completely pulverized and waterfree.
- Lipophilic compounds are extracted by Soxhlet extraction with 100 ml hexane during 10 hours. The extract is concentrated to 5 ml volume and the extracted lipids

are weighted.

A clean-up with florisil column is done (exact quantity of florisil is determined after standardization).Separation of the organochlore compounds is effectuated by two successive elutions: 1) hexane 100 ml and 2) hexane-ether 1/1 100ml.

Determination.

The organoclhorine residues are determined with gaz-liquid chromatography (Packard Instruments model 437),capilar column, electron capture detection, Shimadzu CR 1A integrator, automatic injection LS607, temperature programme

The following technical procedure is used:

injection: splitless with injectorflush after 0.5 min (50 mlN2/min); injection volume: 1 µl; injector temperature 250°C; carrier gaz 0.6 bar N2; bypass 20 ml/min N2; column: fused silica CPSil 8CB (25 m length; 0.22 mm diameter; 0.12 µm film/thickness); oven temperature programme:

- 90°C: 2 min
- 90°-180°C: 20°C/min
- 180-190°C: 2°C/min
- 190°C-220°C: 2°C/min
- 220°C-270°C: 4°C/min
- 270°C: 10 min.

On the obtained chromatograms, PCBs are recognized: 13 peaks of a standard mixture Arochlor 1254 and 9 individual congeners (see further).

Results and discussion.

Identification.

The identification of PCB residues is based on the utilization of two kinds of standardization: firstly by compararing with the standard mixture "Arochor 1254" (this mixture is close to the PCB pattern found in marine samples), and secondly by comparing with nine of the most "classical" PCB congeners, namely 28, 52, 101, 118, 138, 153, 170, 180 and 194, in order of increasing chlorine content (see Fig.7). The chromatogram of the first elution shows clear peaks comparable to the standard mixtures, although more highly chlorinated PCBs are present in the sample than in the 1254 mixture. Such a difference could be explained by the long distance from the sources of PCBs, higher chlorinated isomers being slightly more stable.

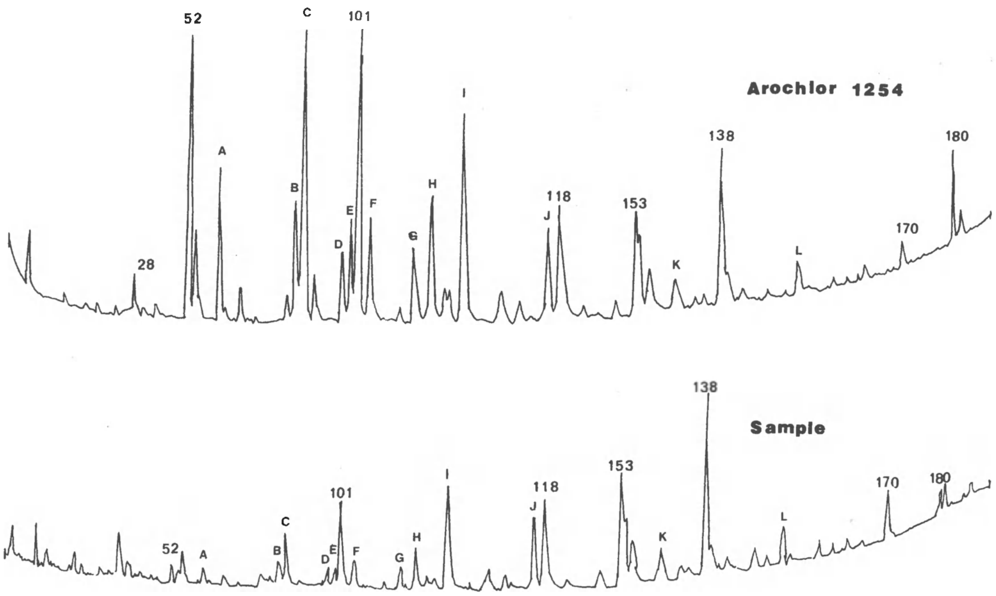

Figure 7: Chromatograms of PCBs in particulate matter and of standard mixtures: Arochlor 1254 (A to L) and individual congeners (28 to 194).

Quantification.

Quantitative evaluation of PCBs constitutes a complex problem, even if most publications do not mention it and avoid the discussion. The first approach makes use of external standardization with an Arochlor 1254 mixture: this "total PCB" concentration is calculated on the basis of the main 13 peaks. Separete congeners can be used as well: the sum of the 9 selected congeners gives an underestimated PCB level; they account for about 33 percent (mean value; min 16 to max 54, n=35) of the "total PCB". Fig.8 shows a strong correlation between the sum of 9 congeners and "total PCB". This correlation also exists for the individual congeners 24 to 180 *versus* "total PCB".

Further in this preliminary discussion, we will consider the concentration of "total PCB" expressed as Arochlor 1254.

Geographical interpretation.

The PCB concentrations have to be expressed in different units system, in order to elucidate the main transfer mechanism (see introduction).

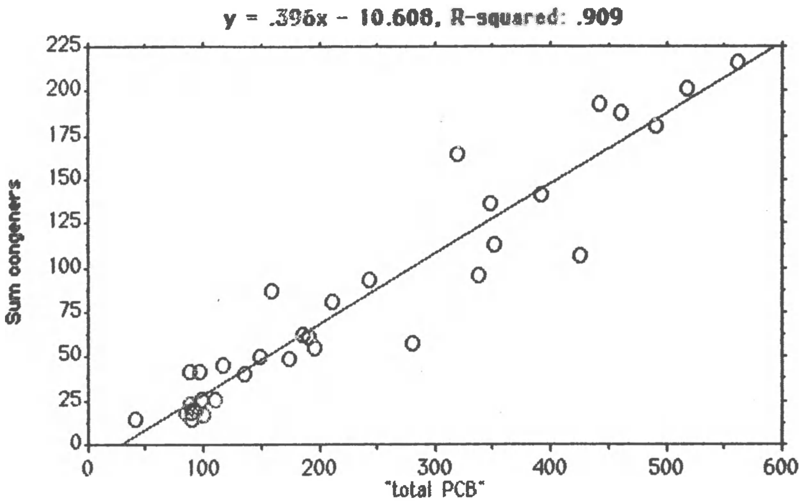

Figure 8: Correlation between "total PCB" (as 1254) and the sum of 9 individual congeners (see text).

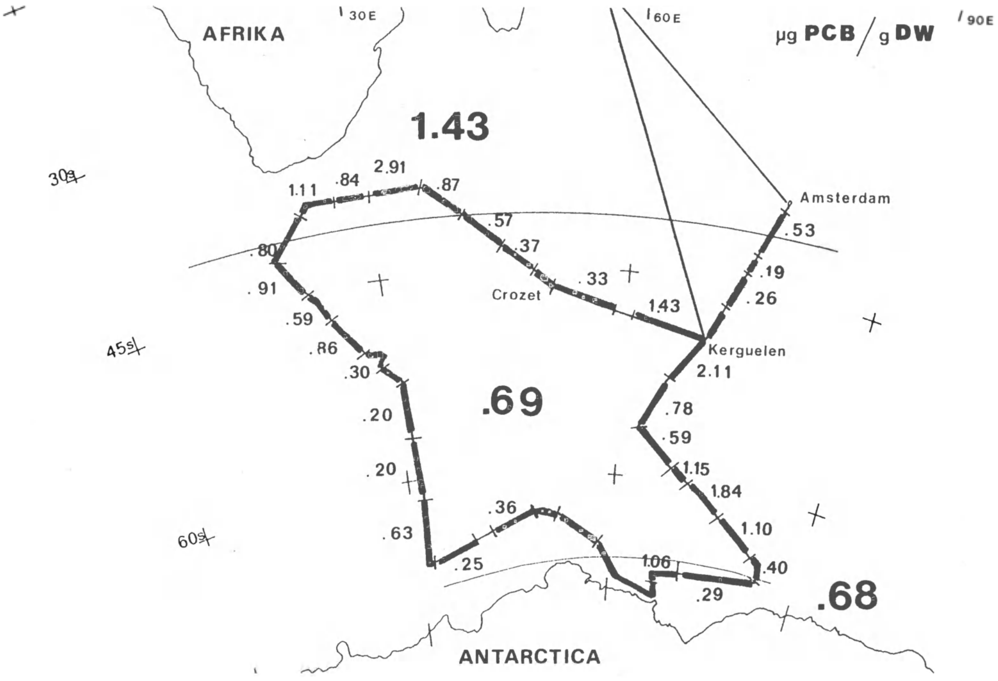

Figure 9: Geographical distribution of PCBs in particulate matter: µg PCB/g dry weight (DW)

Three major zones are compared, as in the chapter on plankton ecology: Subtropical, Antarctic and south of the Divergence. On the basis of dry weight (DW), a slighly higher contamination level is detected in the subtropical zone: 1.43µg PCB/g DW mean value instead of 0.68 in the two other zones (Fig 9).

Expressed per seawater volume (m3) (Fig. 10), no significant difference exists between the three zones: PCB concentration is 1.18 µg/m3 mean value for the whole region.

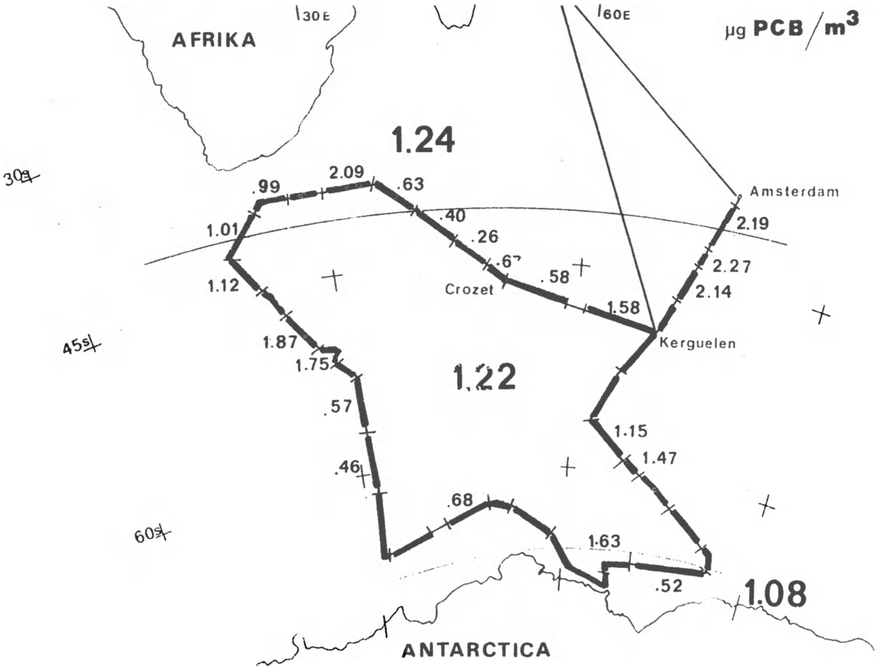

Figure 10: Geographical distribution of PCBs in particulate matter: µg PCB/seawater volume (m3).

Compared with the North Sea ecosystem (Table II) the results indicate a rather high PCB level expressed per dry weight and per fat weight, but per volume the contamination is lower and more constant. These findings are again in favour of the theory obtained in the North Sea, namely that the most important mechanism for particulate matter contamination is adsorption/partition.

Antarctica is indeed less contaminated than our regions but the low biomass causes a high level of PCB per unit of biomass.

All the results discussed so far concern the data on PCBs, obtained in the first elution (see material and methods). Later on, the data of the second elution will allow the discussion of levels of organochlorine pesticides as well. Information like

DDT/DDE and PCB/DDT ratios will provide an important contribution to the discussion of the Antarctic contamination and the origin of these pollutants.

Table II: PCB contamination expressed in different units for the different zones (plus a coastal sample near Kerguelen) (see legend table I and text).

Zone	µg PCB/ DW	µg PCB/ FW	µg PCB/ m^3
Sub-tropical	1.43 *(4)*	24.6 *(4)*	1.24 *(3)*
Antarctic water	0.69 *(22)*	15.4 *(25)*	1.22 *(16)*
S-Divergence	0.68 *(2)*	10.0 *(2)*	1.07 *(2)*
Kerguelen	0.36 *(3)*	20.6 *(3)*	
Total	0.76 *(31)*	16.6 *(34)*	1.18 *(22)*
North Sea	0.40 *(17)*	125.0 *(17)*	6.00 *(17)*

Acknowledgments.

We are very gratefull to the "Terres Australes et Antarctiques Françaises" (TAAF) and to Dr A. Poisson, coordinator, for hospitality on board RV Marion Dufresne during her cruise INDIGO 3.
Marcia Bogaert kindly provided data on particulate carbon.
This text presents research results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsability is assumed by its authors.

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ECOPHYSIOLOGY OF PHYTO- AND BACTERIOPLANKTON GROWTH IN THE PRYDZ BAY AREA DURING THE AUSTRAL SUMMER 1987

Part I : Modelling phytoplankton growth

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

KEYWORDS

Phytoplankton growth, ^{14}C kinetics, mathematical modelling, Southern Ocean, Prydz Bay.

ABSTRACT

A model of phytoplankton growth based on the knowledge of phytoplankton physiology and vertical mixing of surface waters was applied in the Prydz Bay during end-summer 1987. Physiological parameters of the model were experimentally estimated by means of kinetics of phytoplanktonic activities, measurements combining radiotracer technology and classical biochemical methods. Their control by temperature was outlined. It was found that phytoplankton cells of the Prydz Bay were able to grow at their maximal rate between + 2°C and 12°C. An exponential dependence on temperature was however observed in the range -1.8°-+ 2°C. Comparison between field data and predictions of the model run for the different growing conditions encountered by the cells during end-summer in the Prydz Bay indicated that growth and physiological death of phytoplankton were well balanced resulting in no net increase of biomass at this end-summer period. Finally additional runs of the model under the extreme growing conditions of Antarctic phytoplankton has shown that the major trends of variations in phytoplankton biomasses could be predicted by the model.

INTRODUCTION

Among the potential resources of Antarctica its marine living resources are generally considered as those which could possibly lend themselves the best to economic exploitation. The proverbial richness of the Southern Ocean originates from the observation of tremendous biomasses of krill, whales, seals and birds. This *richness* seems however paradoxical since primary production and phytoplankton biomasses as low as in oligotrophic oceanic regions were generally reported in the Southern Ocean in spite of high macronutrients concentrations (see the review by El-Sayed, 1987). It seems therefore difficult to explain how biomass of higher trophic levels can be sustained by oceanic primary production without appealing to other source of phytoplankton biomasses. Indeed some spectacular phytoplankton blooms were occasionally located within the marginal ice zone (El-Sayed, 1971, Smith and Nelson, 1986) and in sea ice microhabitats (Whitaker, 1977, Garrison et al, 1986, Mc Grath Grossi et al, 1987). The enhanced vertical stability of the surface layer resulting from the physical properties of both these particular phytoplankton habitats provides a stable environment with light levels favorable for phytoplankton growth in such a way that biomasses, as high as 190 and 200 μg Chla.l-^{1}, were occasionally recorded within the marginal zone (El-Sayed, 1971) and sea ice (Whitaker, 1977) respectively.

Impact of ice edge blooms could be very important as the extent of the marginal zone covers a wide area. Its contribution to overall primary production is still difficult to evaluate because these blooms are space and time-limited, depending on meteorological conditions. However, preliminary estimates based on occasional primary production field data and on rates of ice retreat indicate that ice edge primary production would increase of more than 60 % the present estimate of Antarctic primary production (Smith and Nelson, 1986).

Also, how much is the contribution of sea ice phytoplankton production is an important question that cannot be answered presently because both the physical and chemical ice habitat and the physiology of ice phytoplankton are still not well known (Garrison et al, 1986).

Because of the variety of habitats in Antarctica (ice, melting ice, oceanic water), accurate estimate of overall primary production should only be provided by means of predictive mathematical model which would take into account the physiology of phytoplankton and its interaction with its habitat. Such a model was developed for temperate coastal waters (Lancelot et al, 1986, submitted). Its applicability to Antarctic environments was tested during an end-summer cruise conducted in the Prydz Bay where the physiological parameters of the above model were experimentally determined.

MATERIAL AND METHODS

Studied area

Sampling stations were visited in the Prydz Bay from February the 14th to March the 23th, 1987. Bathymetry and hydrography of the Prydz Bay are well described in Smith et al (1984). Samples were collected at sunrise at each station from 5 m. depth with a pump. Samples for phytoplankton measurements were stored in the dark at *in situ* temperature until being used. In addition, at those stations where C.T.D. drops were carried out, samples were collected with polyethylene Niskins bottles at 0, 25, 50, 75, 100, 125 and 150 m.

Physical measurements

Vertical structure of the water column was determined for each station from the continuous record of temperature and salinity down to 600 m or the the bottom when shallower. Light profiles were determined by means of an underwater cosine quantum Li-Cor. The vertical light attenuation coefficient was calculated following the Beer Lambert's law. Incident photosynthetically active radiation (P.A.R.) was measured by means of another Li-Cor sensor set up on the superior deck of the ship. Relative losses occuring at sea surface were determined by measurements of incident P.A.R. just above and below the sea surface.

Phytoplankton cellular constituants and activities

Phytoplankton cellular constituants were estimated by regression analysis of measurements of particulate protein, carbohydrates and lipids on chlorophyll a concentrations. Experimental procedures are described in Lancelot-Van Beveren (1980).

Phytoplankton activities -photosynthesis, growth, respiration, excretion- were determined by means of a mathematical model based on elementary cellular biochemistry. This model assumes that synthesis of functional cellular constituants (F)(composed or 80 % of proteins) constitutes the best index of cellular growth. Theoretical basis and experiments supporting it are described in Lancelot et al (1986, submitted).

The structure of the model is illustrated by the diagram of Fig. 1. Three pools of cellular constituants were considered on basis of their biological function : the functional and structural macromolecules F, the reserve products R, composed of lipids and polysaccharides and the small metabolites S, precursors for macromolecules synthesis. Mathematical equations that describe the metabolic processes of their synthesis and catabolism, symbols and units of parameters and variables involved in the equations are listed on Table I.

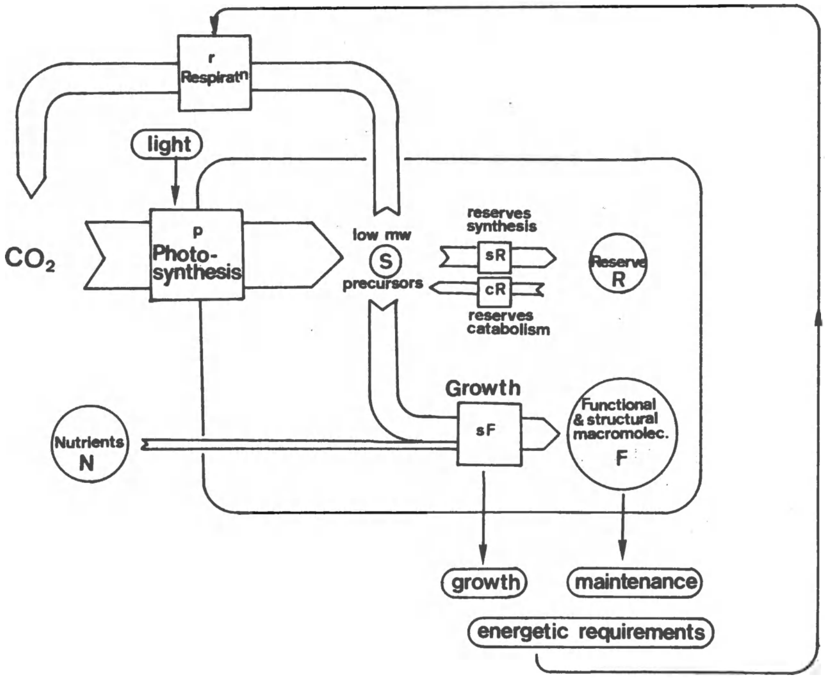


Figure 1 : Diagrammatic representation of phytoplankton cellular constituants and metabolic activities.

Experimental determination of the parameters was carried out based on two kinds of experiments combining radiotracer technology and classical biochemical procedures.

Table I : Mathematical model of phytoplankton growth.

Equations

$$sF = \mu max * \frac{N}{KN + N} * \frac{S}{KS + S} * F \qquad (1)$$

$$p = kmax * (1 - {}^{\frac{\alpha I}{kmax}}) * e^{\frac{-\beta I}{kmax}} * B \qquad (2)$$

$$e = P.E.R. * p \qquad (3)$$

$$sR = \ell max * \frac{S}{KS + S} * R \qquad (4)$$

$$cR = KR * R \qquad (5)$$

$$r = (MAINT * F) + (CESP * sF) \qquad (6)$$

Variables and parameters : symbols and units

Variables	Symbols	Unit
Cellular biomass	B	$\mu gC.l^{-1}$
Functional macromolecules	F	$\mu gC.l^{-1}$
Reserve macromolecules	R	$\mu gC.l^{-1}$
Precursors	S	$\mu gC.l^{-1}$
External nutrients	N	$\mu mole.l^{-1}$

Parameters		
Photosynthetic capacity	α	$h^{-1} (\mu E.m^{-2}.sec^{-1})^{-1}$
Maximal specific rate of photosynthesis	kmax	h^{-1}
Index of photoinhibition	β	$h^{-1} (\mu E.m^{-2}.sec^{-1})^{-1}$
Percentage of excretion	P.E.R.	dimensionless
Maximal specific rate of R synthesis	ℓmax	h^{-1}
Constant of R catabolism	KR	h^{-1}
Maximal specific rate of F synthesis	μmax	h^{-1}
Half-saturation constant of N assimilation	KN	$\mu mole.l^{-1}$
Half-saturation constant of S assimilation	KS	$\mu gC.l^{-1}$
Constant of maintenance of basal metabolism	MAINT	h^{-1}
Energetic costs for F synthesis	CESP	dimensionless

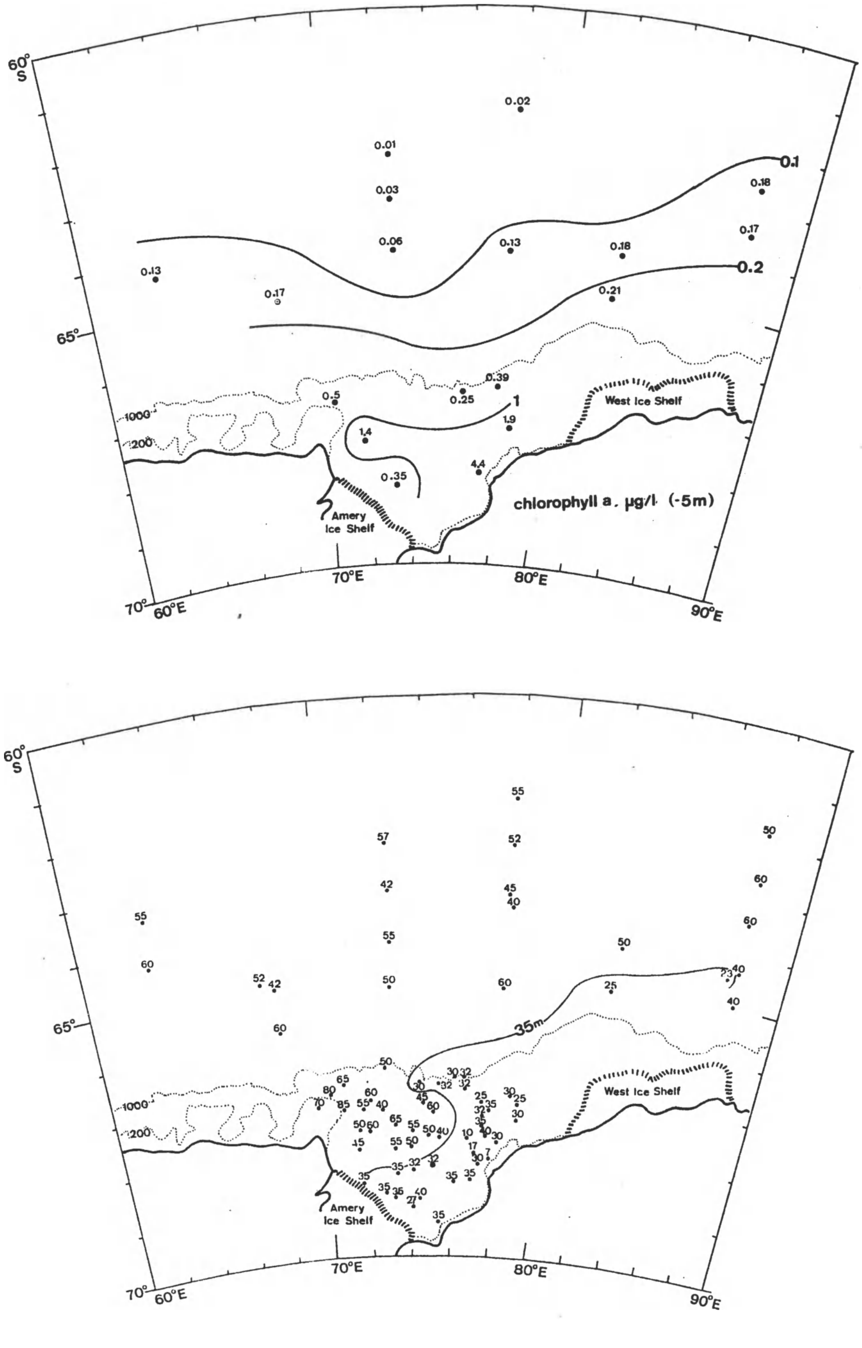
(i) the experimental determination of photosynthetic parameters involved short-term ^{14}C incubation - Steemann-Nielsen standard method - performed at different light intensities. Photosynthetic parameters kmax, α, β were then statistically estimated by means of Platt et al (1980)'s equation.

(ii) the experimental determination of growth parameters was performed by mathematical adjustment based on the results of long-term kinetics of ^{14}C assimilation into 4 pools of cellular constituants easily separable by simple biochemical procedures: lipids, small metabolites, polysaccharides and proteins (see below).
^{14}C incubation were carried out in a thermostatic growth cabinet illuminated by artificial light (maximal P.A.R. = 135 $\mu E.m^{-2}.sec.^{-1}$). Experimental procedure and biochemical fractionation are those described in Lancelot and Mathot (1985).

RESULTS AND DISCUSSION

End-summer phytoplankton in the Prydz Bay : level and growing conditions

Chlorophyll a concentrations measured during February-March 1987 in the Prydz Bay and in the northern open waters are reported on Fig.2a. Significantly higher concentrations were measured in shelf waters although chlorophyll a concentrations were very low offshore in agreement with data generally reported for this area (Painting et al, 1985; Fukui et al,1986). On the other hand vertical mixing (Fig 2b) was less intense in the coastal area suggesting an inverse correlation between the two variables. Temperature was found to range between -1.8° and + 2°C and nutrients concentrations were far above saturation.



<u>Figure 2</u> : Spatial distribution of a) chlorophyll a concentrations and b) depths of the mixed layer in the Prydz Bay during February-March 1987.

Physiological parameters of the model and their control by temperature

Fig. 3ab shows an example of the experimental determination of the parameters that characterize respectively photosynthesis and phytoplankton growth processes. Values of parameters and initial conditions are reported on Table II.

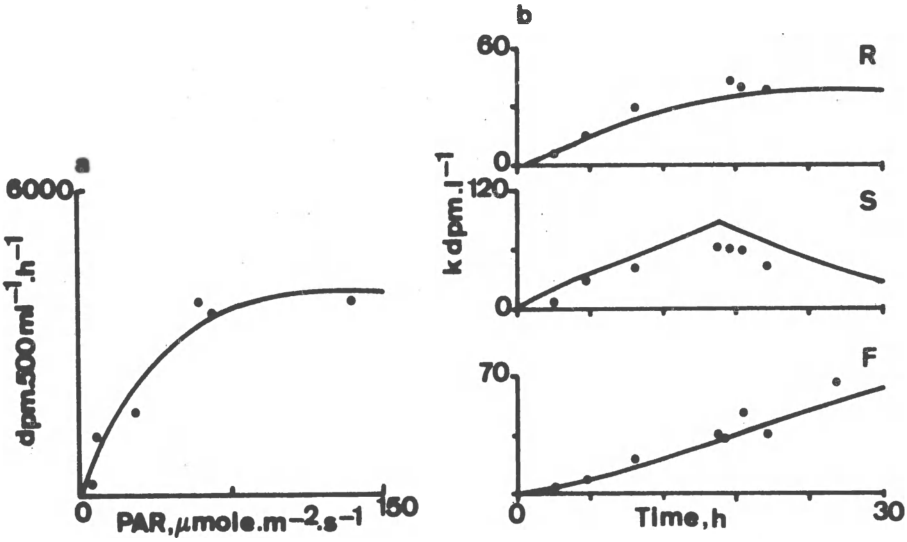


Figure 3 : Physiological characteristics of a phytoplanktonic community sampled at 64°04S, 91°29E on February 15th 1987 :
a. Relationship between photosynthesis and light
b. Kinetics of ^{14}C assimilation into R, S and F cellular phytoplanktonic constituants during a 17 : 7 light:dark cycle : prediction curves and experimental data.

Examination of Fig.3 indicates good agreement between the prediction of the model and the experimental data relative to the assimilation of ^{14}C into R, S and F cellular constituants. Validation of the model used for calculating phytoplankton daily growth was provided by Fig. 4 which shows results from several runs of the model using identical sets of parameters for different photoperiods along with the corresponding experimental data.

Table II : Initial conditions and physiological parameters characteristical of a phytoplankton community sampled in February 1987 at station 64°04S, 91°29E.

Initial conditions		
F	311	$\mu gC.l^{-1}$
R	0.5	"
S	16	"
N	13	$\mu mole.l^{-1}$

Parameters	
α	$1.6.10^{-4}\ h^{-1}.(\mu E.m^{-2}.sec^{-1})^{-1}$
kmax	$9.10^{-3}\ h^{-1}$
β	$10^{-9}\ h^{-1}\ (\mu E.m^{-2}.sec^{-1})^{-1}$
P.E.R.	0.05
KR	$0.12\ h^{-1}$
μmax	$8.10^{-3}\ h^{-1}$
KN	$4\ \mu mole.l^{-1}$
KS	$15\ \mu gC.l^{-1}$
MAINT	$10^{-3}\ h^{-1}$
CESP	0.32

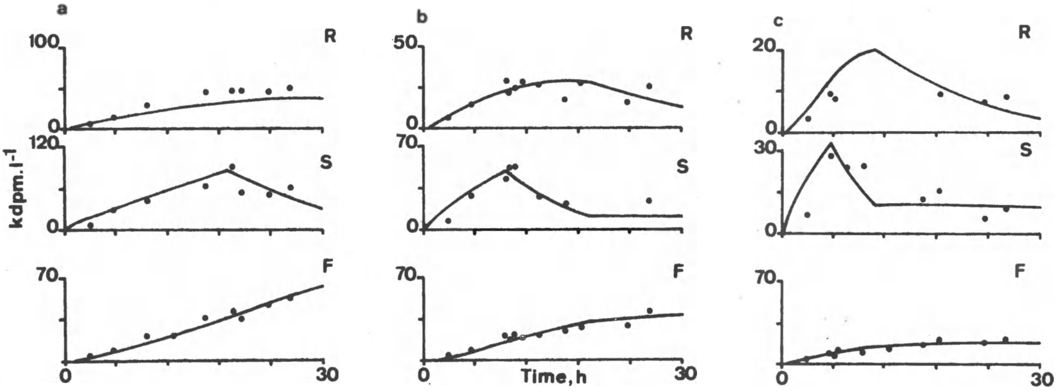


Figure 4 : Kinetics of ^{14}C assimilation into R, S and F cellular constituants during a. 19: 5 light:dark cycle
b. 10:14 light:dark cycle
c. 6:18 light:dark cycle

Parameters of the model were determined for different stations in the Prydz Bay and their control by temperature was investigated. This environmental variable controls mostly three parameters : the maximum specific photosynthesis kmax, the maximum specific growth rate μmax and the maintenance constant MAINT.

Two types of adaptations to temperature were considered as recommended by Precht (1958) : Resistance adaptation, on one hand, which refers to mechanisms that determine the upper and lower temperature extremes limiting growth, and capacity adaptation, on the other, which occurs at temperature between the extremes and is described by a particular kinetics.

Resistance adaptation to temperature of end-summer phytoplankton of the Prydz Bay can be seen on Fig. 5ab which shows the dependence of kmax and μmax respectively for a range of temperature between -2 and + 21°C.

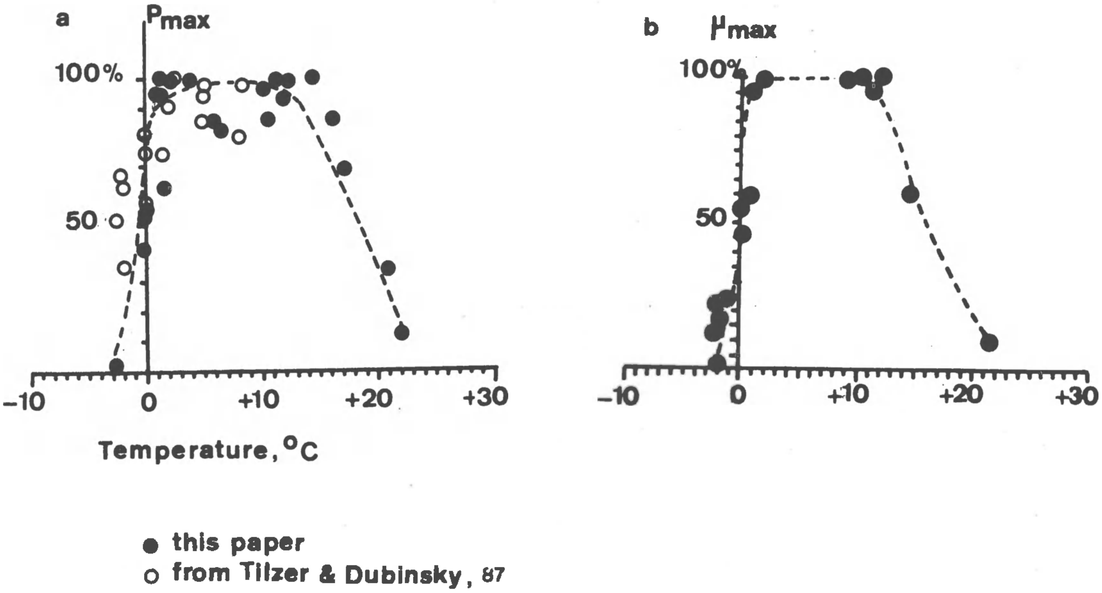


Figure 5 : Relationship between a) kmax and b) μmax and temperature : results expressed in % of maximal rate.

This figure shows clearly that end-summer Antarctic phytoplankton is able to photo-synthetize and grow at its maximal rate when temperature ranges between + 1 and 11°C, in agreement with Tilzer and Dubinsky's (1987) results. Below and above these temperatures, kmax values decrease very sharply in agreement with similar data obtained by Neori and Holm-Hansen (1982) in the western Scotia Sea and Bransfield Strait.

Capacity adaptation to temperature on the other hand can be seen on Fig.6 which suggests an exponential dependence of kmax on *in situ* temperature.

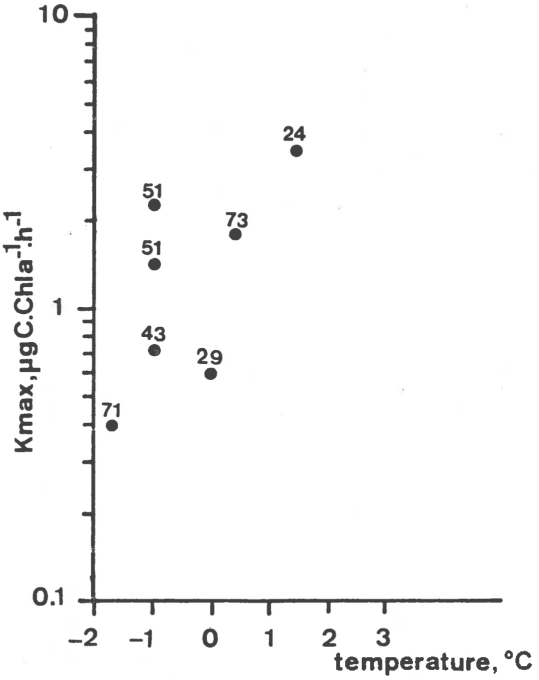


Figure 6 : Relationship between kmax and *in situ* temperature.

The maintenance constant is mostly determined by adjustement of experimental data as illustrated by Fig.3. Its dependence on temperature is therefore not obvious. However, under extreme temperature of - 1.8°C, maintenance could be estimated from the catabolism rate of storage products as deduced from data reported on Fig. 7. Indeed dark protein synthesis does not proceed at this low temperature and respiration ensures the only maintenance of basal metabolism.

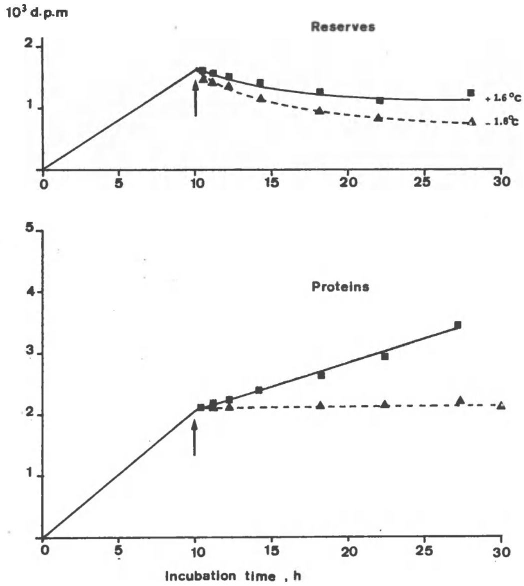


Figure 7 : Kinetics of ^{14}C dark assimilation into storage products and proteins by Prydz Bay phytoplankton incubated at + 1.6° and -1.8°C (dotted line). Previous photoperiod = 10 h.

Phytoplankton growth in the Antarctic environment

Vertical mixing is known to have an important impact on the environment experienced by phytoplankton cells (Lewis et al, 1984) and numerous authors now claim that extreme conditions of turbulence together with low temperature are at origin of the phytoplanktonic scarcity of Southern Ocean (Whitaker, 1977, El-Sayed and Tagushi, 1981, El-Sayed, 1984, 1987, Priddle et al, 1986). Inversely, the high vertical stability induced by melting waters contributes to provide high biomasses of phytoplankton in the marginal ice zone. Indeed following values of δ, the ratio between euphotic and mixing depth, phytoplankton will spend more or less time in the aphotic layer. Depending on its own physiology, phytoplankton will therefore grow, maintain, autocatabolize or ultimately die depending on the size of photosynthetized storage products i.e. the previous light history of the cells.

The control of phytoplankton growth by variations in intensity of vertical mixing was established for an end-summer phytoplanktonic community of the Prydz Bay by means of the mathematical model previously described. Daily specific rates of growth and physiological death by phytoplankton were calculated by integration of equations gathered on table I on the variations of P.A.R. and on the depth down to the depth of the mixed layer. Values of parameters are those reported on table II. The model assumes in addition that vertical motion within the mixed layer is very fast, ensuring an identical light history to the whole phytoplanktonic community (cf. Lewis et al, 1984). Results of these calculations are illustrated by Fig. 8a.

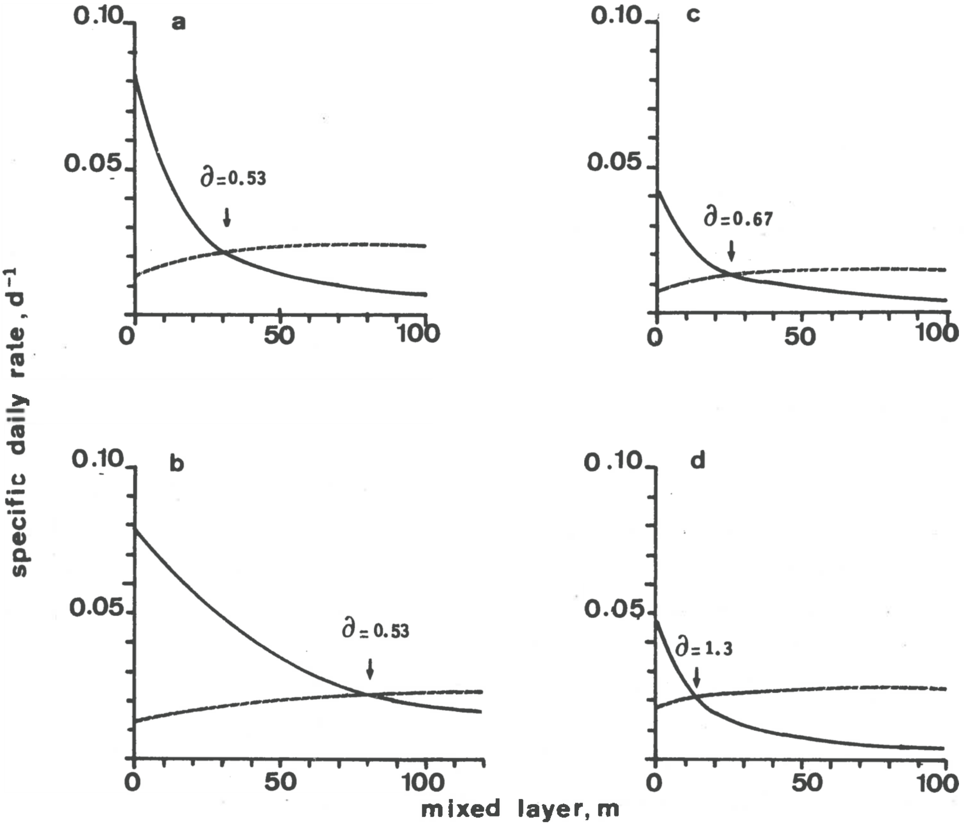


Figure 8 : Daily specific growth rate and physiological death (dotted line) calculated for different depths of the mixed layer under different growing condition

a) $\eta = 0.29$ m^{-1} photoperiod Φ = 17 h T° 1°C.
b) $\eta = 0.1$ m^{-1} Φ = 17 h T° 1°C
c) $\eta = 0.29$ m^{-1} Φ = 13 h T° 1°C
d) $\eta = 0.29$ m^{-1} Φ = 17 h T° -1.8°C

It shows that specific daily growth decreases exponentially when mixed layer becomes deeper, although specific daily physiological death increases slowly with depth and stabilizes as a consequence of the simultaneous decrease in phytoplankton biomass. The critical depth, i.e. the depth where growth compensates exactly physiological death on a daily average, occurs under these particular growing conditions at -30 m corresponding to a δ value of 0.53. Results from several runs of the model under different growing conditions as change in optical properties of the water column (Fig. 8b), changes in daily P.A.R. (Fig. 8c), decrease in temperature corresponding to decrease in kmax, μmax, MAINT (Fig. 8d) show that critical depth is determined by both the depth of the mixed layer, the optical properties of the water column and the physiology of phytoplankton. This constrasts with Sverdrup's (1953) hypothesis assuming a single control by vertical stability.

From these predictions and assuming that optical properties of the water column are mostly dependent on the biomass of phytoplankton and that the physiological characteristics of the phytoplanktonic community remain identical, it is possible to calculate the steady-state biomass of the phytoplankton community growing in a large range of mixed layers reproducing ice edge system on the one hand and oceanic one on the other. Results of these calculations as illustrated by Fig.9 show an asymptotical dependence of steady-state phytoplankton biomass on the depth of the mixed layer.

At shallow mixed layer as in marginal zone, steady-state biomass tends to fabulous concentrations of chl.a, in perfect agreement with the concentration of 190 μgChl.l-^{1} recorded by El-Sayed (1971) in surface waters of the Weddell Sea. Inversely at high depth of mixed layer, steady-state biomass tends to undetectable concentrations of chl.a as usually recorded in the oceanic area (cf. El-Sayed, 1987).

Validation of the mathematical model developed for prediction of phytoplankton growth was finally supported by Fig. 9b which shows comparison between prediction curves of steady-state biomass calculated for extreme conditions of temperature and light encountered by phytoplankton cells during end-summer in the Prydz Bay and the field data reported on Fig.2a. Perfect agreement between prediction curves and field data indicates that from a physiological point of view growth and death of phytoplankton are well-balanced in the Prydz Bay during this end-summer period. No net increase of phytoplankton biomass should therefore be observed at this period.

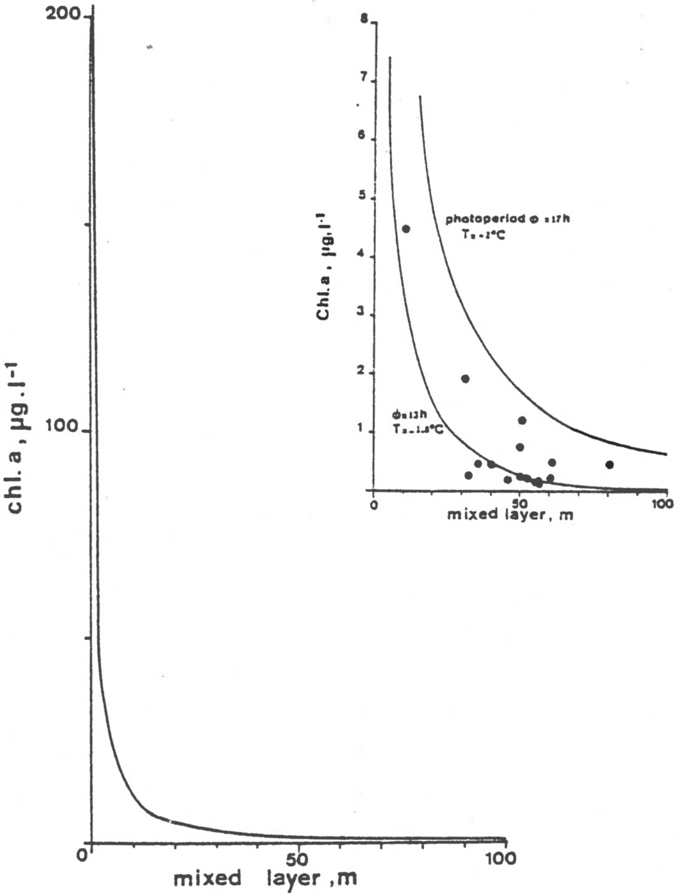


Figure 9 : Relationship between steady-state phytoplankton biomass and depth of the mixed layer.

CONCLUSIONS

Simulation experiments of phytoplankton growth described above indicate that we have developed a conceptual mathematical model of phytoplankton growth able to predict the major trends of the variations in Antarctic phytoplankton, on basis of the knowledge of the growth physiology of phytoplankton and the vertical mixing of surface waters.

This model represents therefore an important tool for the overall estimate of primary production of the Antarctic ecosystems. Better knowledge of phytoplankton physiology in the different antarctic habitats (water, ice melting, ice) together with development of hydrodynamical models for the prediction of vertical mixing of surface waters and ice progression and retreating rates would allow to further refine this model. It will then permit a priori calculation of primary production in the different habitats, an information essential for the understanding of the ecological functioning of the Antarctic ecosystem. This will be the purpose of our future work on Antarctica phytoplankton.

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ECOPHYSIOLOGY OF PHYTO- AND BACTERIOPLANKTON GROWTH IN THE PRYDZ BAY AREA DURING THE AUSTRAL SUMMER 1987

Part II : Bacterioplankton activity

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

KEYWORDS

Heterotrophic bacteria, growth rates, thymidine incorporation, Southern Ocean, Prydz Bay.

ABSTRACT

In order to assess the quantitative role of heterotrophic bacterial activity in the cycling of primary produced organic matter, measurements of bacterial biomass, growth and mortality rates were carried out in the Prydz Bay area in February - March 1987. These measurements, along with data from other authors collected in the same area allow to reconcile contradictory opinions published in the literature concerning the significance of the microbial loop in the Antarctic ecosystem in comparizon with temperate marine systems:

(i) A similar significant part of primary production is utilized by planktonic heterotrophioc bacteria.

(ii) A much longer delay in the response of bacteria to phytoplankton development exists in Antarctica.

These results are discussed in the light of the ecological structure of the Antarctic Ecosystem.

INTRODUCTION

In most marine ecosystems, a significant fraction of primary production is channelled into the pool of dissolved organic matter and utilized by planktonic bacteria instead of being grazed by herbivores (Pomeroy, 1974; Williams, 1981; Joiris et al, 1982; Azam et al, 1983). This microbial loop has not been intensively studied in the Antarctic seas and its role in the overall function of the ecosystem is still a matter of controversy. Although several authors (Hodson et al, 1981; Hanson et al, 1983) reported measurements of microbial activities in the Antarctic Ocean of the same order of magnitude as those observed in temperate areas, others (Kriss et al, 1969;

Sorokin, 1971; Pomeroy and Deibel, 1986) claimed that a dramatic decrease of bacterial activity occurs at temperature below 2°C, leaving a larger part of primary production available for grazing by herbivores.

We developed a general methodology for measuring and understanding the control of bacterial activity in aquatic environments. Our approach is based on the direct measurement of some basic processes involved in bacterial dynamics (Billen and Fontigny, 1987; Billen et al, 1988). Our purpose was to check the applicability of this approach to Antarctic waters and to try to resolve the present controversy regarding the role of bacterial activity in Antarctic waters.

METHODS

Measurements were carried out on board of the MV Nella Dan in the Prydz Bay area during voyage 7 of the Australian Natianal Antarctic Research Expeditions, from 14th February to 23th March 1987.

Bacterial Biomass determination

Bacterial biomass was determined by epifluorescence microscopy after acridine orange staining according to the procedure of Hobbie et al (1977). Biovolumes were visually estimated by comparison with a calibrated grid. Except in few instances of very high bacterial densities, where larger cells were observed, the bacterial volume was generally between 0.020 and 0.07 μm^3. Biomass was calculated from biovolume, using a conversion factor of 1.2 10^{-7} $\mu gC/\mu m^3$ (Watson et al, 1977).

Thymidine incorporation and bacterial growth rate measurements

Thymidine incorporation into cold TCA insoluble material was measured following the procedure of Fuhrman and Azam (1982). Thymidine incorporation rate was converted into bacterial production by using a conversion factor of 5 10^9 cells/nmol thymidine. This factor was determined for our own site by following both cell number increase and thymidine incorporation in .2 μ filter sterilized surface water reinoculated with 2 μ filtered water and incubated at 2-4°C. Carbon production rate was calculated from cell production, taking into account the mean cell volume determined microscopically and the same biomass/biovolume ratio as used for biomass calculations.

Specific growth rates (μ) were determined as the ratio between bacterial production and biomass. Note that this ratio is independant on the conversion factor chosen for converting cell numbers into biomass.

Bacterial mortality

The rate of bacterial mortality was estimated according to a procedure modified from that developed by Servais et al (1985). A sample was incubated for about 24 h. at *in situ* temperature with 25 nmole/l (methyl-H^3)-thymidine. It was then put for 10-20 h. in a dialysis bag in a flow of seawater, in order to eliminate the unincorporated thymidine. The disappearance of radioactivity from the DNA of the bacteria was then followed for about 50 h. A linear decrease was observed in semilog plot, the slope of which give the first order specific mortality coefficient (kd).

RESULTS and DISCUSSION

Bacterial biomass - chlorophyll a relationship.

Both vertical (Fig. 1) and geographical (Fig. 2) distributions of bacterial biomass observed in Prydz Bay in February-March 1987 suggest a close control by phytoplankton. Much higher biomasses exist above the pycnocline than below and the highest values in the upper layer are found in the areas characterized by a shallow mixed layer, which were shown above to be able of sustaining higher phytoplankton biomasses.

This correlation between bacterial and phytoplankton biomasses is classical in most temperate aquatic environments (Bird and Kalf, 1984). Several authors, however, did not found it back in the Southern Ocean. Thus, Mullins and Priddle (1987) observed only low bacterial biomasses, without any

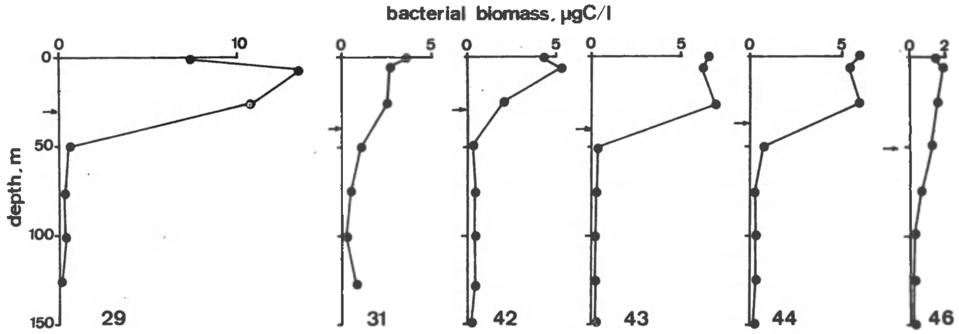

Figure 1. Vertical distribution of bacterial biomass observed in Prydz Bay in Febr.-March 1987. The arrow indicate the depth of the pycnocline.

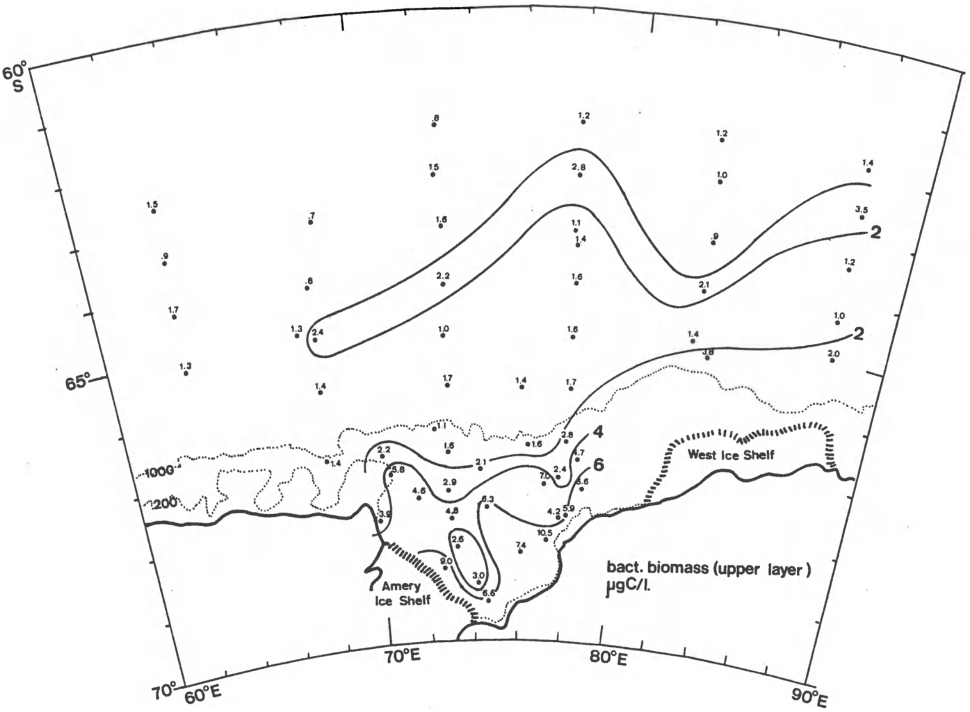

Figure 2. Geographical distribution of bacterial biomass observed in the upper mixed layer in Prydz Bay in February-March 1987.

relationship with phytoplankton in the Bransfield Strait in end-January. So did Davidson (1984) in mid-December off Prydz Bay. Similarly, the data collected in Prydz Bay by our Belgian colleagues on board of the Marion Dufresne in mid-January (Joiris et al, this volume) do not show any significant relationship between the low bacterial biomass and the comparatively high chlorophyll a concentrations (Fig. 3). Our data in February, for their part, shows a clear relationship with chlorophyll a, with much higher bacterial biomass (Fig. 3). In March, phytoplankton biomasses are much lower, but bacteria remain at high concentrations, in good agreement with the data collected in beginning February by Painting et al (1985) in the same area (Fig. 3).

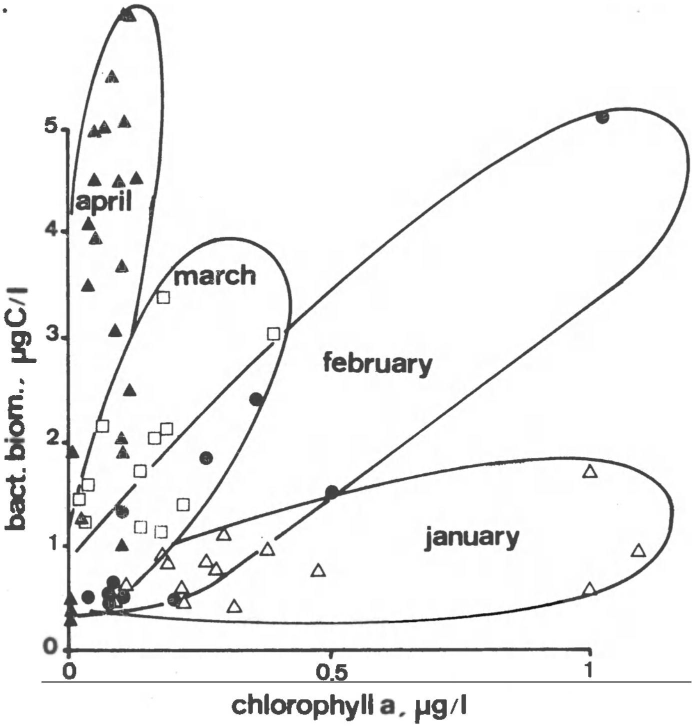

Figure 3. Relationship observed between bacterial biomass and chlorophyll a concentration in Prydz Bay at different times of the ice-free period. (△) January, Joiris et al, this volume; (●) February and (□) March, own observations; (▲) early April, Painting et al, 1985.

Put together, all these apparently contradictory data are easily reconciled : they indicate the existence of a delayed relationship between

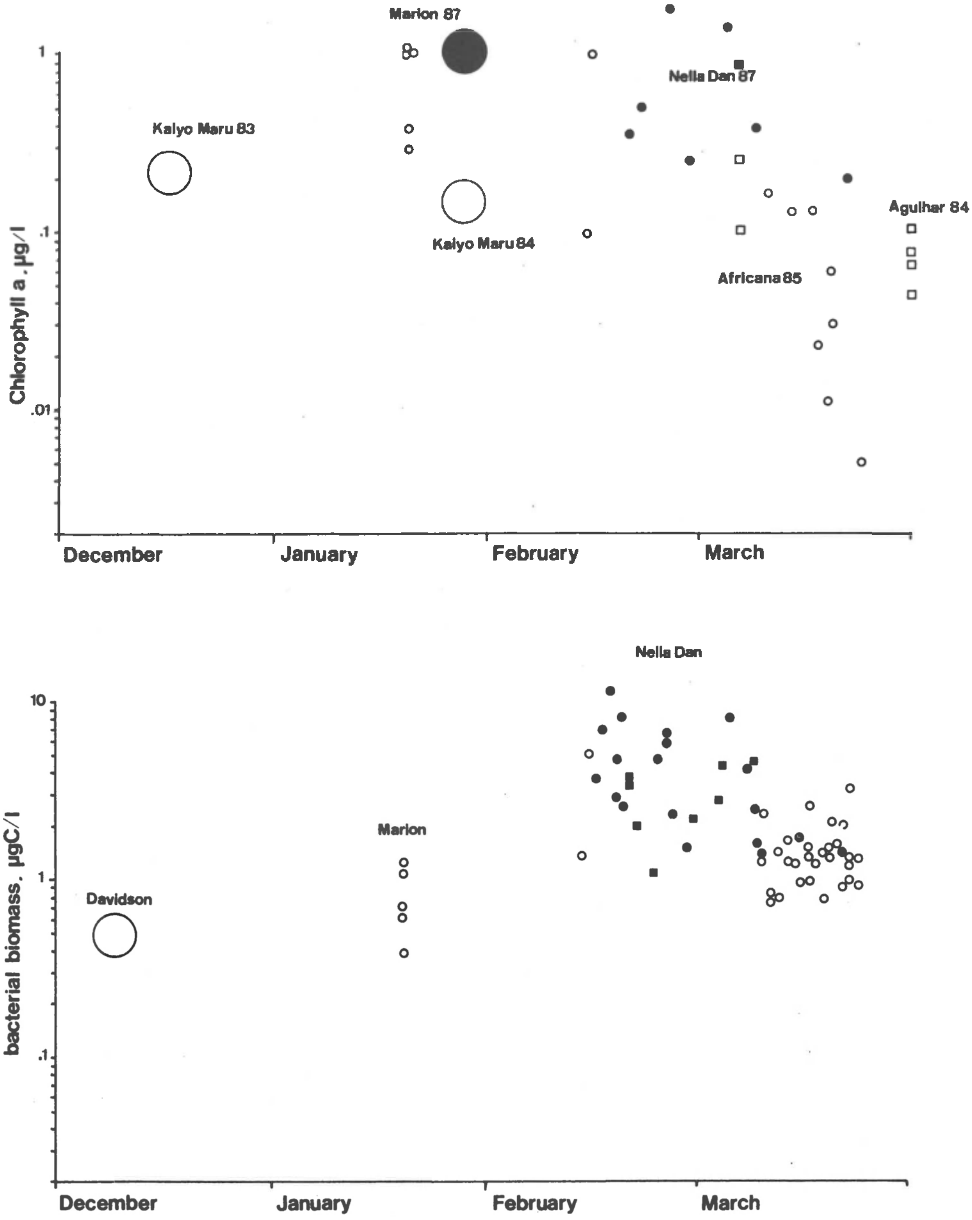

Figure 4. Seasonal variations of chlorophyll a and bacterial biomass in the inshore (closed symbols) and offshore (open symbols) zones of Prydz Bay. Data from our own observations and from Joiris et al (this volume), Hecq and Goffart (this volume), Davidson (1985), Fukui et al (1986), Painting et al (1985), Miller (1986).

phytoplankton and bacteria. Such a delay was already described in the North Sea (Billen & Fontigny, 1987; Billen et al, 1988), were the peak of bacterioplankton follows the phytoplankton spring bloom by about 10 days. The data summarized in figure 4 shows that the delay between phytoplanktonic and bacterial peak is of about 1 month in Antarctica, the former occuring in early February, the latter in early March.

2.2. Bacterial growth and mortality rates.

In order to further characterize the dynamics of bacterioplankton populations in Prydz Bay, measurements of the fluxes of production and mortality, which together govern the variations of bacterial biomass, have been carried out.

Bacterial production rates in the upper mixed layer are the highest in the Eastern inshore area (.100 - .300 μgC/l.h). In the offshore zone, they range beween .02 - .04 μgC/l.h. A regular decrease is observed in all areas untill the end of March, when production rates have dropped by nearly two orders of magnitude.

The ratio of production rate to bacterial biomass gives the specific growth rate (μ) (Fig. 5). The highest values observed in Antarctica are quite similar to those observed in temperate marine systems (see eg Billen et al, 1988), in spite of the low temperatures. They decrease regularly from mid-February to end-March.

Mortality rates, on the other hand, seem much more constant during this period, as also shown in Fig. 5. These values are significantly lower than the specific mortality rate constants found in temperate marine systems (Billen et al, 1988), indicating a slower turnover rate of bacterial biomass in the Southern Ocean.

Growth rates are clearly higher than mortality in February, corroborating our conclusion that the bacterial population is actively growing at that time. End-March, specific growth rates are very close to, or lower than mortality rates, indicating a declining bacterial population.

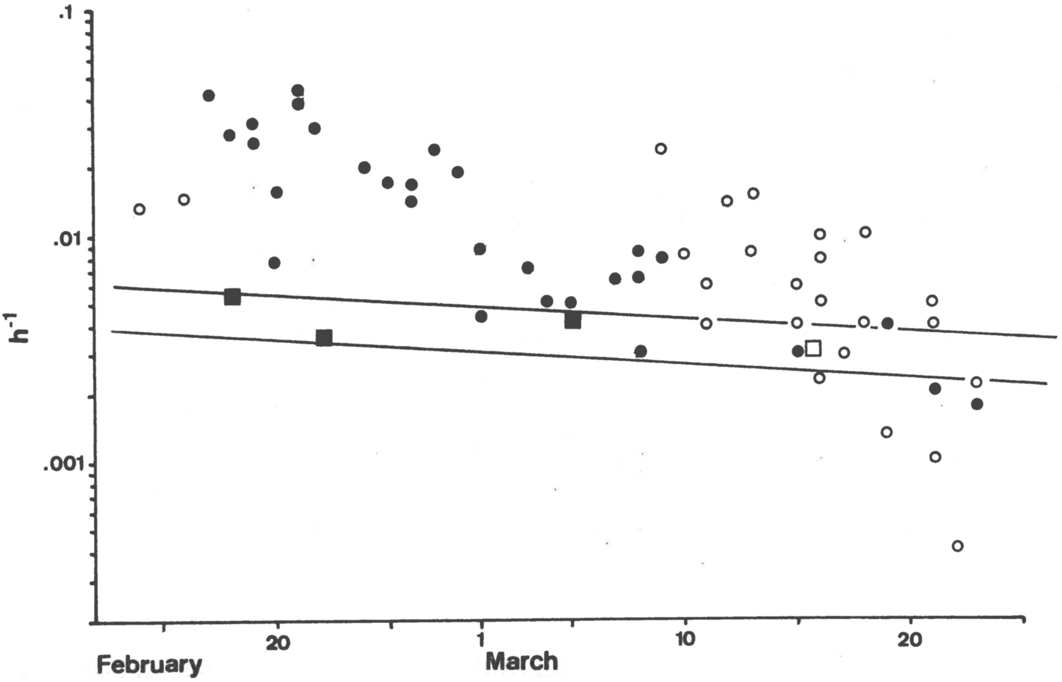

Figure 5. Specific bacterial growth (circles) and mortality rates (squares) observed in the inshore (closed symbols) and offshore (open symbols) zone of Prydz Bay in February-March 1987.

2.3. Quantitative importance of the bacterial loop in organic matter cycling.

Our biomass and production measurements in Prydz Bay, along with those recorded in the literature for the same area, allow a first estimate of the budget of organic matter at the first trophic levels during the ice-free period (i.e. from January to end-March for the inshore area and from December to mid-April for the offshore zone). The figures and hypothesis leading to these estimations are presented in Table I. Except for values in brackets, which are best guess estimates, the figures of bacterial biomass and specific growth rates mentionned in this table are the rounded means of the observations made by ourselves or by other authors and discussed in this paper. Bacterial production figures were then calculated from these data.

Table I. : Tentative budget of organic matter cycling in Prydz Bay during the ice free period.

mixed layer	**Eastern Inshore area** 30m			**Offshore area** 50m		
	bact.biom. (µgC/l)	µ (h^{-1})	bact.prod. ($mgC/m^2.d$)	bact.biom. (µgC/l)	µ (h^{-1})	bact.prod ($mgC/m^2.d$)
DEC	-	-	-	.5	(.01)	(6)
JAN	(.5)	(.035)	13	.8	(.02)	19
FEB	4	.03	85	2.5	.014	42
MAR	2	.008	12	1.5	.006	10
APR	-	-	-	1.5	.006	10
bact.prod. (gC/m^2.period)			3.3			2.5

In the absence of nutrient limitation, a growth yield of .3 is a reasonable estimate for heterotrophic bacteria (Lancelot & Billen, 1986; Servais et al, 1987). Based on this, the total flux of primary produced organic matter flowing through the bacterial compartment can be estimated to 11 and 8 gC/m^2.period for the inshore and the offshore zones respectively. At the present time, we have no estimation of primary production in Prydz Bay for the same periods. From literature data (Treguer and Jacques, 1986; El Sayed, 1984) a reasonable range of 20-60 and 10-20 gC/m^2.period can be assumed for the two zones respectively. This would imply that about 20-55% and 40-80% of the organic matter made available by phytoplankton growth is used by microheterotrophs in the inshore and offshore areas respectively.

Thus, the overall importance of the microbial loop does not differ a lot in the Southern Ocean from what has been observed in temperate marine systems, in good agreement with the previous conclusions of Hodson et al (1981) and Hanson et al (1983). However, a much longer delay in the response of bacteria to phytoplankton development has been evidenced by our observations. This long delay could explain the conclusion reached by other authors that bacteria do not play a significant role in the utilization of primary produced organic matter in Antarctic waters, based on observations made mostly at the early stage of the vegetation season.

CONCLUSIONS

Our study of the first trophic levels of the Antarctic ecosystem allow to derive some general conclusions concerning its overall functioning in connection to the apparent paradox of the abundance of higher organisms in the Southern Ocean.

We confirmed that this apparent richness is not caused by an exceptionnaly high primary production. During summer, when light intensity, photoperiod and nutrient concentrations are at high levels, primary production is mostly controlled by the vertical mixing of the water column. This results in low phytoplanktonic biomass and production in most open sea areas, while very high biomass and production values can be locally and temporarily reached in areas where the water column is stabilized.

Similarly, the "richness" of the Southern Ocean is not to be explained -as suggested by some authors (Pomeroy and Deibel, 1986)- by a generally low activity of heterotrophic microorganisms, leaving most of the primary production available to grazers. The microbial loop quantitatively plays the same role in the Antarctic marine ecosystem as in temperate environments.

The high biomasses of organisms belonging to the Krill-vertebrates food chain is therefore not the result of a particularly high availability of vegetal organic matter. It rather results from two adaptations of higher organisms in Antarctica.

Firstly, their ability to efficiently use, at a large geographical scale, resources of local and temporary nature. Most of the higher organisms, from krill to whale, are indeed characterized by a very high mobility.

Secondly, their ecophysiological K-strategy, in which most resources are devoted to reserve accumulation, aimed to ensure a minimal maintenance during long starvation periods, while reproduction is kept to a very low rate.

These characteristics result in an extreme fragility of the Antarctic ecosytem. Its richness is only apparent: the large stocks, being only slowly replaced, cannot necessarily sustain intensive exploitation.

ACKNOWLEDGEMENTS

The preceding text present results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy office). The scientific responsibility is assumed by its authors. We are greatly indebted to the Australian Antarctic Division for the kind invitation to take part to the MV Nella Dan Voyage 7 of the 1986-1987 Australian National Antarctic Research Expeditions to Prydz Bay. Collaboration on board with Dr. S. Wright and D. Thomas was greatly appreciated. G. Billen is Research Associate of the FNRS (Fonds National de la Recherche Scientifique).

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DISTRIBUTION OF PHYTOPLANKTONIC PARAMETERS IN THE INDIAN SECTOR OF THE SOUTHERN OCEAN DURING INDIGO III CRUISE

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

Phytoplankton and watermasses.

KEYWORDS

Chlorophyll-a - Frontal Systems - HPLC - Southern Ocean - Watermasses.

ABSTRACT

The distribution of chlorophyll-a obtained by HPLC along vertical and horizontal profiles during Indigo III cruise in the Indian sector of the Southern Ocean was used to correlate the phytoplankton and watermasses patterns .

They confirm that the Southern Ocean is not ecologically uniform as is implied by the general term "Antarctic and Subantarctic Ecosystem" (Hempel,1985).

Highest chlorophyll-a standing crops are associated with the main frontal systems (the Subtropical Convergence, the Antarctic Polar Front and the Antarctic Divergence).

In these particular areas, significant amounts of living phytoplankton are found as far as 70 meters deep, suggesting a downwards transport of chlorophyll-a along isopycnals, in relation with the frontal hydrodynamics.

In interfrontal areas, chlorophyll-a concentrations are generally very low and restricted to the upper layers of the water column.

Therefore, the vertical distribution of phytoplankton in the Southern Ocean is not as uniform as expected, referring to El Sayed (1978) or to Jacques et Minas (1981).

These preliminar results show that a more intensive and detailed study of the antarctic frontal systems might lead to a better understanding of the phytoplankton distribution and productivity.

INTRODUCTION

Recent studies on phytoplankton distribution in the Southern Ocean have shown a wide geographical variation of chlorophyll-a standing crops (Jacques et Minas,1981; Lutjeharms _et al._,1985;

Taniguchi,1986).
In fact, the Southern Ocean is not ecologically uniform as is implied by the general term "Antarctic and Subantarctic Ecosystem". (Hempel,1985).

At the surface, phytoplankton communities distribution in the antarctic and subantarctic areas is characterized by a high spatial and temporal heterogeneity related to watermasses pattern.
The highest chlorophyll-a concentrations occur below the permanent pack-ice zone. Maximum surface concentrations vary from 7.01 to 11.30 mg chl.a/m^3 in late January (Fukuchi et al.,1985).
High levels of chlorophyll-a are associated with sea-surface fronts wherever such frontal systems have the characteristics of a convergence (Lutjeharms et al.,1985). They are observed at the Subtropical Convergence, at the Antarctic Polar Front and at the Continental Water Boundary (Continental Convergence). Highest chlorophyll-a concentrations reach respectively 0.6 - 1.5 mg chl.a/m^3 at the Subtropical Convergence (Lutjeharms et al.,1985; Furuya et al.,1986), 1.5 mg chl.a/m^3 at the Antarctic Polar Front (Lutjeharms et al.,1985) and more than 2 mg chl.a/m^3 at the Continental Water Boundary (Lutjeharms et al.,1985). Maximum values occur generally in January.
Smaller increases of the chlorophyll-a concentration may be observed at the Subantarctic Polar Front (Lutjeharms et al.,1985) and around 60°S, in the Antarctic Surface Water, where surface warming increases the stability in the upper 80 meters of the water column significantly (Jacques et Minas,1981; Lutjeharms et al.,1985).
In the other areas, phytoplankton biomass is close to those observed in oligotrophic waters (0.1 - 0.3 mg chl.a/m^3) (Jacques et Minas,1981).

The vertical distribution of phytoplankton biomass in the Southern Ocean is generally uniform within the euphotic zone (El Sayed,1978) although subsurface maxima in chlorophyll around 40 meters depths are not uncommon (Jacques et Minas,1981; Furuya et al.,1986).

In this work, we report geographical distribution of the living phytoplankton during the austral summer in relation to watermasses pattern observed during Indigo III cruise, in the Indian sector of the Antarctic Ocean.

MATERIALS AND METHODS

Data were collected on board of the R.V."MARION DUFRESNE" (TAAF) during the INDIGO III cruise from January 3rd to February 27th, 1987.
The cruise track covered the Indian Sector of Antarctica, between latitudes 38°S to 67°S and longitudes 18°E to 84°E (Fig.1).

Salinity and temperature were determined on board by Dr.A.Poisson's INDIGO III research team [1].

Nitrate, silicate and phosphate concentrations were analysed with Technicon II Autoanalyser Systems, respectively by Dr. F.Dehairs [2] and L.Goeyens [2](NO_3) and by DR.A.POISSON's INDIGO III research team [1](SiO_2 and PO_4).

Chlorophyll-a was determined directly on board of the ship by the authors, using a High-Performance Liquid Chromatograph (HPLC).
At every station, seawater was sampled at ten depths from surface to 200 meters.
Between Antarctica and South Africa (Stations 87 to 98), surface seawater sampling was carried out at 2 hours intervals to picture the spatial variability on a finer scale of chlorophyll-a distribution.
Chlorophyll-a was determined by filtration of 2 or 3 liters of seawater through Whatman GF/C glass fiber filters, with extraction by pulverization in 70% acetone. 200 μl of the extracts were injected into a LKB HPLC Chromatograph, using a C_{18} Chromospher column. Chromatographic separation of pigments was obtained by linear gradient elution from 75% acetonitrile to 90% acetone in 30

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minutes. Total flow rate was 1 ml/min. The absorbance was mesured at 430 nm and peaks area calculated by Intersmat integrator. Commercial chlorophyll-a was obtained from Sigma for calibration and measurement precision was 20 ng chl.a/m^3.

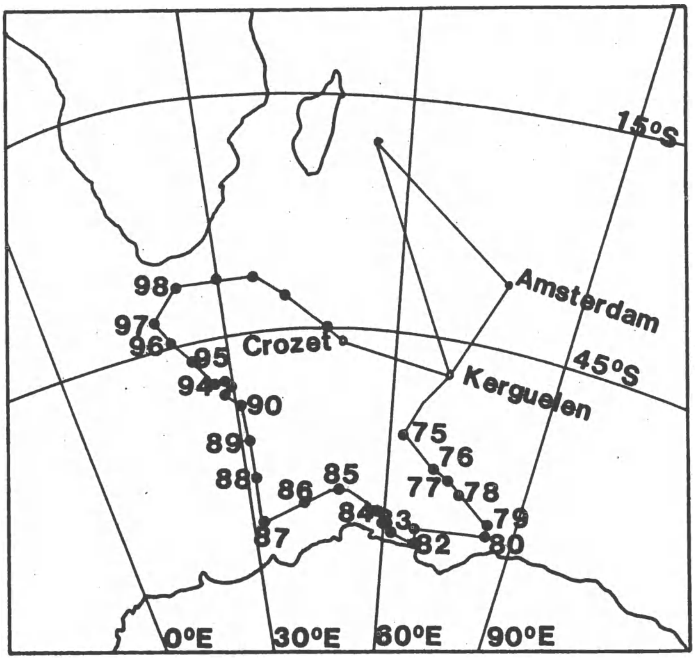

Fig.1: INDIGO III cruise track.

RESULTS

From the complete data set, we consider three separate tracks, identified as the western track (Stations 98 to 87), the eastern track (Stations 75 to 80) and the southern track (Stations 87 to 80) - Fig.2.

3.1 WESTERN TRACK.

3.1.1 Horizontal distribution of watermasses

The section through the watermasses between Africa and Antarctica shows three distinct frontal systems : the Subtropical Convergence, the Subantarctic Front and the Antarctic Polar Front (Antarctic Convergence).

Phytoplankton and watermasses.

The characteristics, location and nature of each these fronts are discussed below, in turn, for the Indian sector of the Southern Ocean and compared with results of the horizontal sea-surface track.

THE SUBTROPICAL CONVERGENCE

This front, the most northerly of those evident in Fig.2 shows a sharp transition between Subtropical Surface Water thermally enhanced by Agulhas Current Water (Lutjeharms <u>et al.</u>,1985) and Subantarctic Surface Water.
On average, the Subtropical Convergence lies between 41°S (Lutjeharms,1985) and 46°45'S (Furuya <u>et al.</u>,1986). She exhibits the strongest horizontal thermal and saline gradients both at the sea-surface and at depth. At the sea-surface, mean temperature drops from 17.9°C to 10.6°C (Lutjeharms and Valentine,1984) and an average decrease in salinity of 0.7 °/oo is recognisable (from 35.1 °/oo to 34.4 °/oo)(Furuya <u>et al.</u>,1986). Increases in reactive nitrate and phosphate of 8.7 and 0.60 µgat/l have also been observed (Allanson <u>et al.</u>,1981).

During Indigo III cruise, the surface gradient of the Subtropical Convergence was lying at a mean latitude of 41°S. Drops in temperature and salinity of 6.85°C and 0.69 °/oo have occured between 39°54'S (20.35°C - 35.15 °/oo) and 42°08'S (13.50°C - 34.46 °/oo) - Fig.2 -.
Between Stations 98 and 96 (situated on each side of the Subtropical Convergence), increases in nitrate and phosphate of 16.7 and 1.0 µgat/l have been mesured at the sea-surface - Fig.4 -.

THE SUBANTARCTIC POLAR FRONT

This front, located in the Subantarctic Surface Water, may be recognized at the sea-surface by an average decrease in temperature of 3.9°C at a mean latitude of 46°23'S (Lutjeharms <u>et al.</u>,1985).

During Indigo III, the surface expression of the Subantarctic Polar Front has been observed between 46°24'S and 47°34'S. Temperature and salinity drop respectively to 3.85°C and 0.19 °/oo.

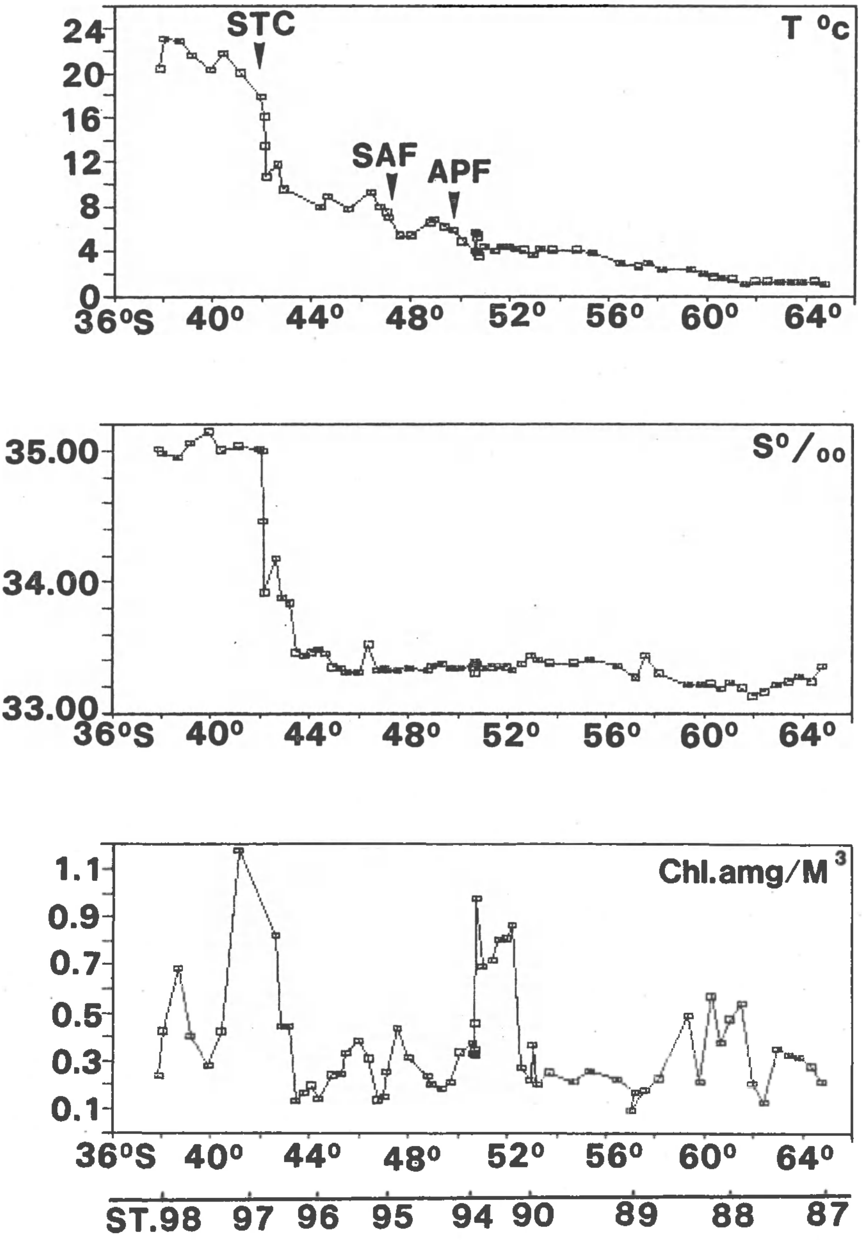

Fig.2: Distribution of temperature* (°C), salinity* (°/oo) and chlorophyll-a concentration (mg chl.a/m^3) at the sea-surface along the western track between Africa and Antarctica. The locations of the Subtropical Convergence (STC), Subantarctic Front (SAF) and Antarctic Polar Front (APF) are indicated according their sea-surface characteristics.

* : A.Poisson's INDIGO III research team data.

THE ANTARCTIC POLAR FRONT (ANTARCTIC CONVERGENCE)

Generally considered to consist of a confluence of Antarctic Surface Water and Subantarctic Surface Water, the Antarctic Polar Front is found on an average latitude of 50°18'S (Lutjeharms et al.,1985).
The average temperature drop is 1.8°C and the salinity shows no significant gradient (Lutjeharms, 1985).

Surface expression of this front has been found between 48°54'S and 50°44'S. Temperature decrease was 3.2°C but salinity was nearly constant on both sides of the Convergence. In the area of this front, sharp increases of surface nitrate and silicate concentrations have been observed (Fig.4).

3.1.2 Vertical structure of watermasses

Isopycnals distribution obtained from the data collected at the stations is shown in Figure 3, from surface to 200 meters deep.

Between 38°S and 50°S, subsurface expression of the three frontal systems discussed above is easily recognisable.

As opposed to the other watermasses, the Antarctic Surface Water (Stations 90 to 87) is stratified, especially in the southern part of the track (Station 87), where a sharp pycnocline is found between 30 and 40 meters deep. Between 62°S and 66°S, strongly sloping isopycnals are proceeding towards the surface, probably due to the vicinity of the Antarctic Divergence. Highest values in silicate are observed at the Station 87 : 48.7 µgat/l at surface, 73.4 µgat/l at 100 meters deep (Fig.4).

3.1.3 Chlorophyll-a distribution

Along the horizontal track through the watermasses between Africa and Antarctica, two major peaks in chlorophyll-a concentrations are observed at the sea-surface: one at the Subtropical Convergence; other, at the Antarctic Polar Front (Fig.2).

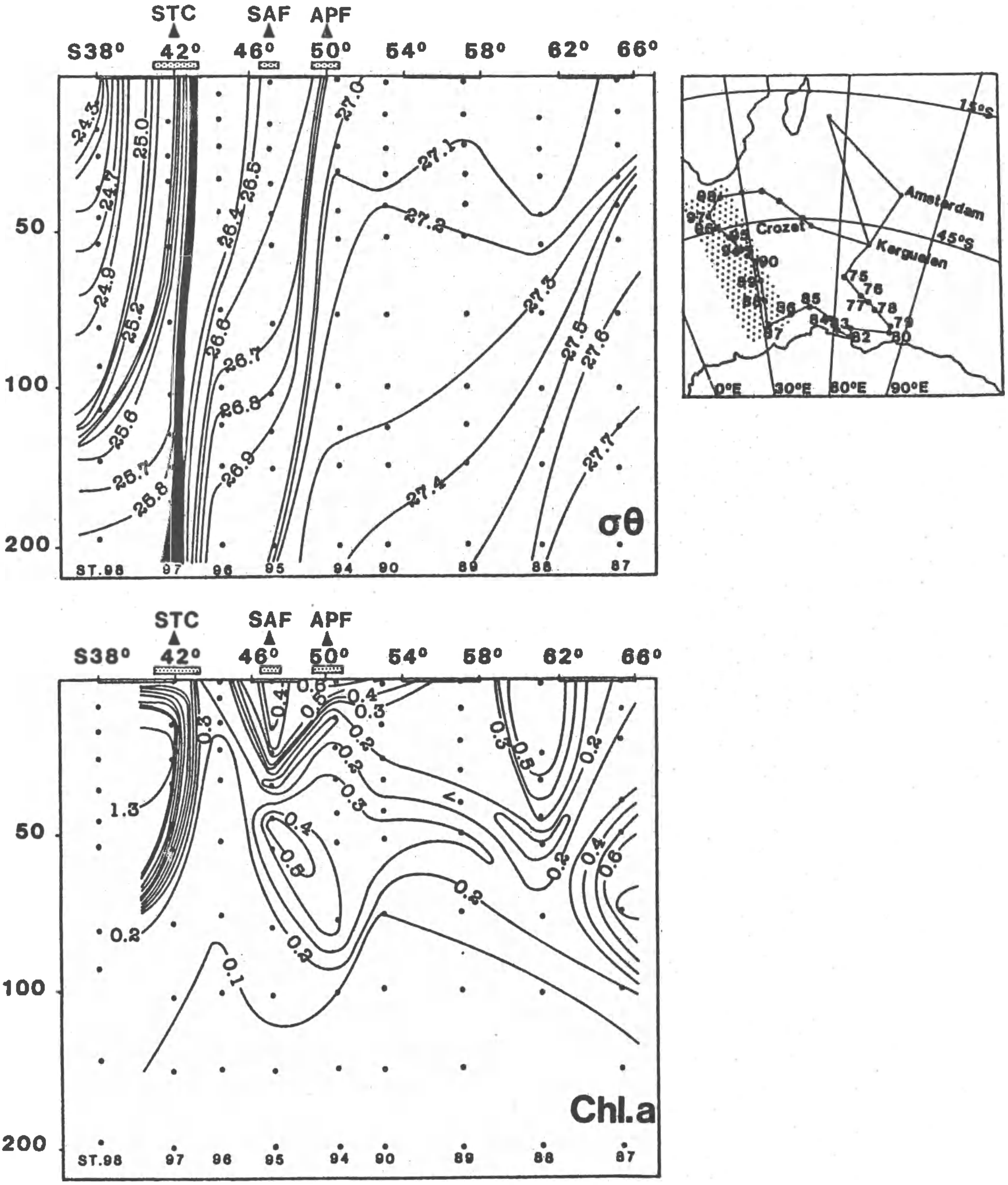

Fig.3: Vertical distribution of density (σ_θ) and chlorophyll-a concentration (mg chl.a/m^3) from surface to 200 meters deep along the western track (Stations 98 to 87). Density has been calculated from temperature and salinity data of A.Poisson's INDIGO III research team.

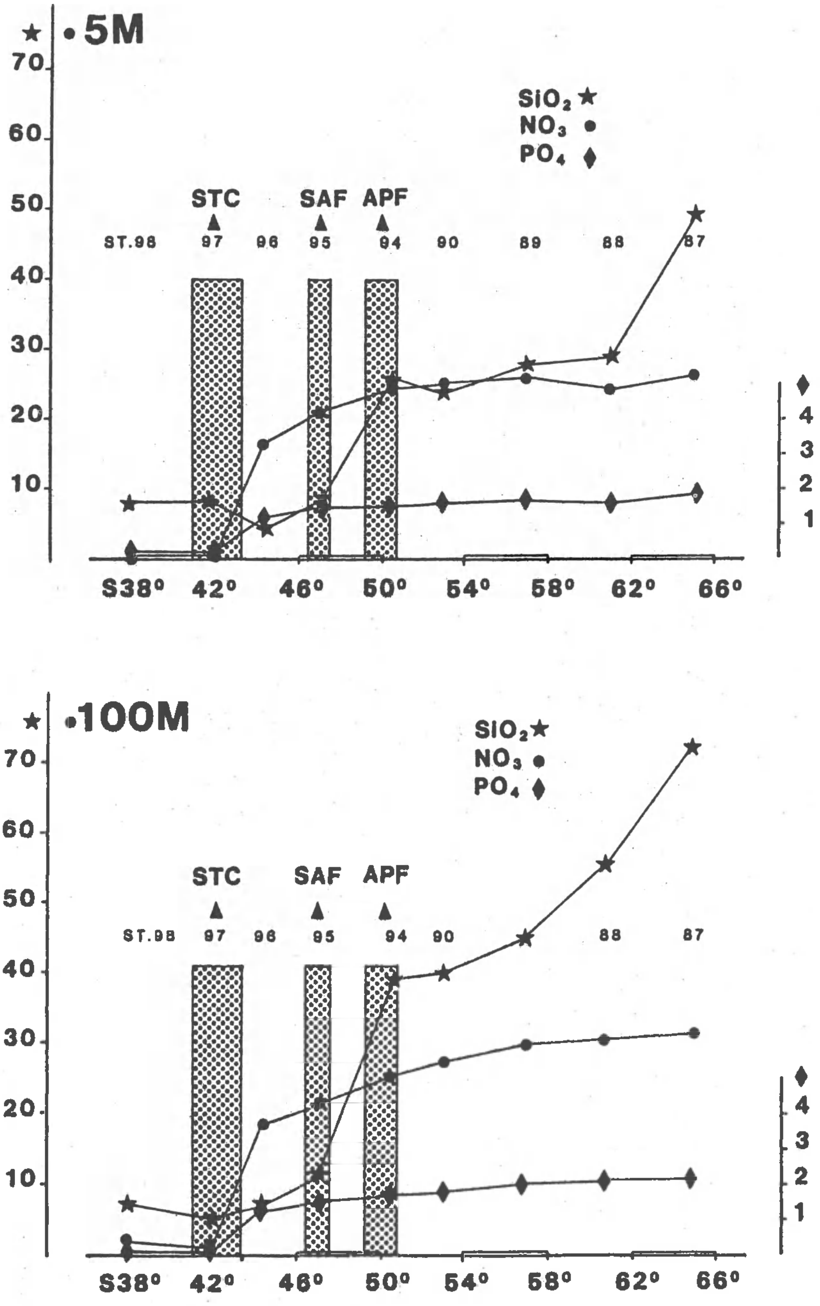

Fig.4: Horizontal distribution of reactive phosphate, silicate and nitrate at the sea-surface and at 100 meters deep (μgat/l) along the western track (Stations 98 to 87). Data obtained from A.Poisson's INDIGO III research team (PO_4 and SiO_2) and F.Dehairs and L.Goeyens (NO_3).

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At the Subtropical Convergence, surface chlorophyll-a concentration reaches 1.18 mg chl.a/m^3. Further to the north, a smaller increase in chlorophyll-a occurs (0.69 mg chl.a/m^3).At the Station 97, situated on the Subtropical Convergence, concentrations greater than 1.0 mg chl.a/m^3 are found up to 70 meters deep (Fig.3).
At south of the Antarctic Polar Front, surface chlorophyll-a concentration reachs 0.98 mg chl.a/m^3 (Fig.2).

In the area of the Subantarctic Polar Front, two significant peaks (0.44 and 0.38 mg chl.a/m^3) occur on each side of the gradient (Fig.2).

Within the Subantarctic Frontal Zone and the Antarctic Convergence area, the vertical structure of phytoplankton distribution is not well documented because of stations removal. However, below the surface chlorophyll-a maximum, a subsurface phytoplankton peak (0.4-0.5 mg chl.a/m^3) is found between 50 and 75 meters deep (Fig.3).

In the Antarctic Surface Water, an increase in chlorophyll-a (0.28-0.57 mg chl.a/m^3) is observed over a wide latitudinal zone between 58°S and 64°S from the surface to a maximum of 40 meters deep (Fig.2 & 3).

At the southern limit of this track, a maximum subsurface (0.4-0.7 mg chl.a/m^3) occurs between 40 and 95 meters deep (Fig.3).

3.2 EASTERN TRACK.

3.2.1 Hydrological data

Hydrological structure of this section, situated in the Antarctic Surface Water, is shown at Fig.5.
She corresponds obviously to that described above for the western track between 54°S and 66°S (Stations 90 to 87).
At the Station 80, a sharp pycnocline, resulting from isopycnals constriction occurs around 20 meters deep. At this station, very high values in silicate are observed, both at the sea-surface and at 100 meters deep (respectively 42.8 and 73.4 μgat/l -Fig.6-).

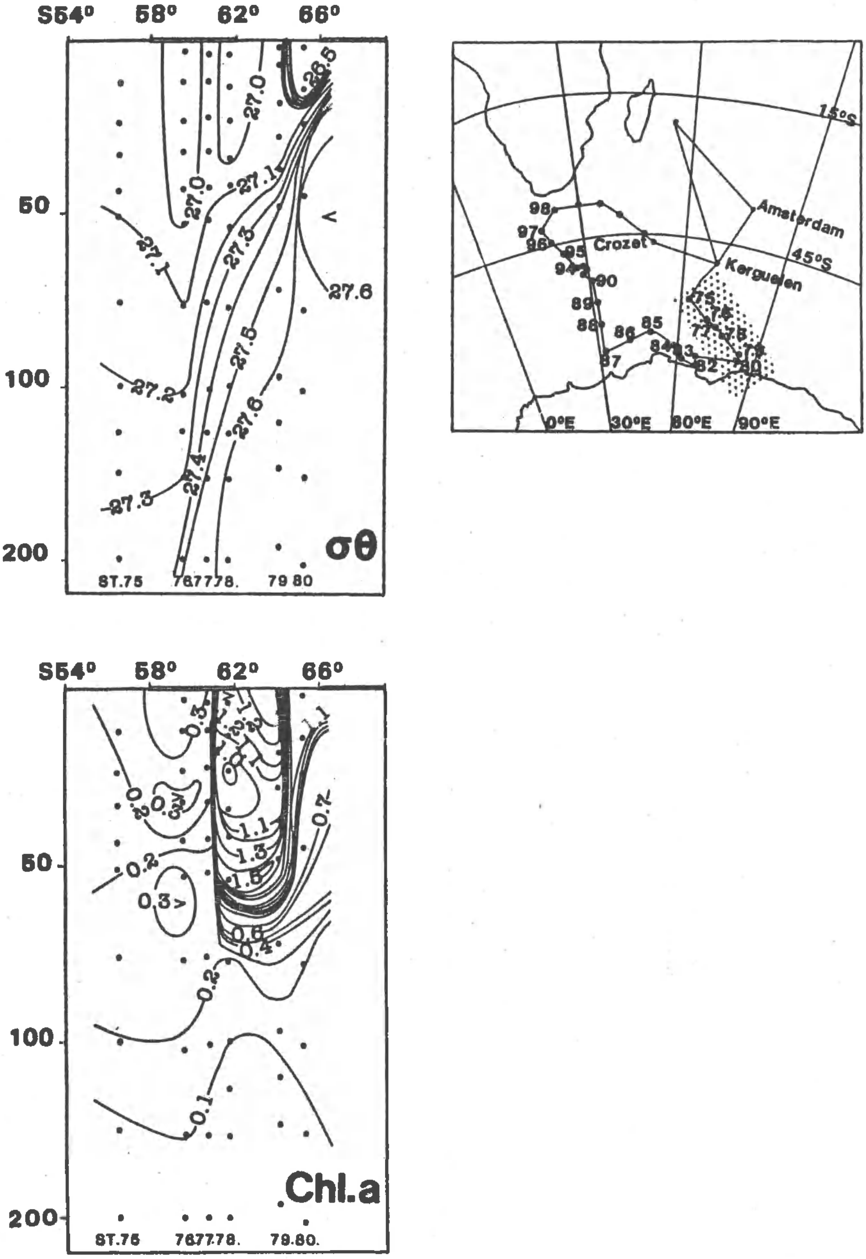

Fig.5: Vertical distribution of density (σ_θ) and chlorophyll-a concentration (mg chl.a/m^3) from the surface to 200 meters deep along the eastern track (Stations 75 to 80). Density has been calculated from temperature and salinity data of A.Poisson's INDIGO III research team.

Like at Station 87, these facts suggest the vicinity of the Antarctic Divergence.

3.2.2 Chlorophyll-a distribution

Investigations performed at the stations from surface to 200 meters deep show a strong heterogeneity in chlorophyll-a distribution related to hydrological structure (Fig.5)

Maximum chlorophyll-a concentrations (more than 1.0 mg chl.a/m^3) occur in the southern part of the track, between 10 meters deep at Station 80 and 65 meters deep at Station 78.
In fact, phytoplankton distribution follows the general slope of isopycnals, between Stations 80 and 78. At this station, living chlorophyll-a seems to be accumulated around 55 meters deep where highest phytoplankton biomass (more than 1.5 mg chl.a/m^3) is observed.

Everywhere else along this section, chlorophyll-a concentration is close to those observed in oligotrophic waters (less than 0.2 mg chl.a/m^3).

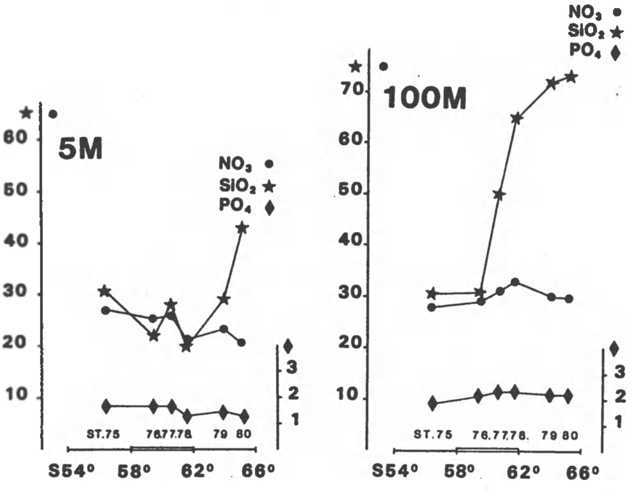

Fig.6 :Horizontal distribution of reactive phosphate, silicate and nitrate at the sea-surface and at 100 meters deep (µgat/l) along the eastern track (Stations 75 to 80). Data obtained from A.Poisson's INDIGO III reseach team (PO_4 and SiO_2) and F.Dehairs and L.Goeyens (NO_3).

3.3 SOUTHERN TRACK.

3.3.1 Hydrological data

Density distribution between longitudes 32°E to 84°E and latitudes 62°S to 67°S is presented in Fig.7.
As observed previously in the Antarctic Surface Water, isopycnals are proceeding towards the surface, from the most northern station (Station 85 -62°20'S-) to the southern stations (Station 87 -65°11'S- at the west side of the section and Station 80 -65°10'S- at the east side of the section).

Highest silicate concentrations are associated to the most southern stations, except for the Station 80, where surface concentration's decrease is probably correlated to the high phytoplankton biomass -Fig.8-.

3.3.2 Chlorophyll-a distribution

Two maxima in phytoplankton biomasses are recorded along this section : one westwards, below the pycnocline (0.4-0.7 mg chl.a/m^3) and other over a wide latitudinal zone, between 60°E and 84°E -Fig.7-. In this area, high levels in chlorophyll-a concentration (0.5-1.1 mg chl.a/m^3) occur above the pycnocline. Between Stations 83 and 84, living chlorophyll-a seems to be carried along the isopycnals so far as 100 meters deep.

Between these two areas of phytoplankton accumulation, chlorophyll-a concentration is very low (0.1 mg chl.a/m^3).

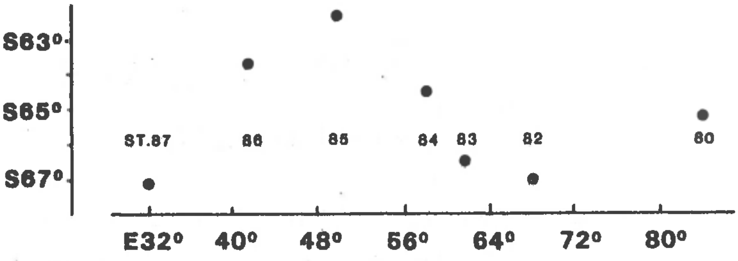

Fig.7A: Latitudinal position of the stations along the southern track.

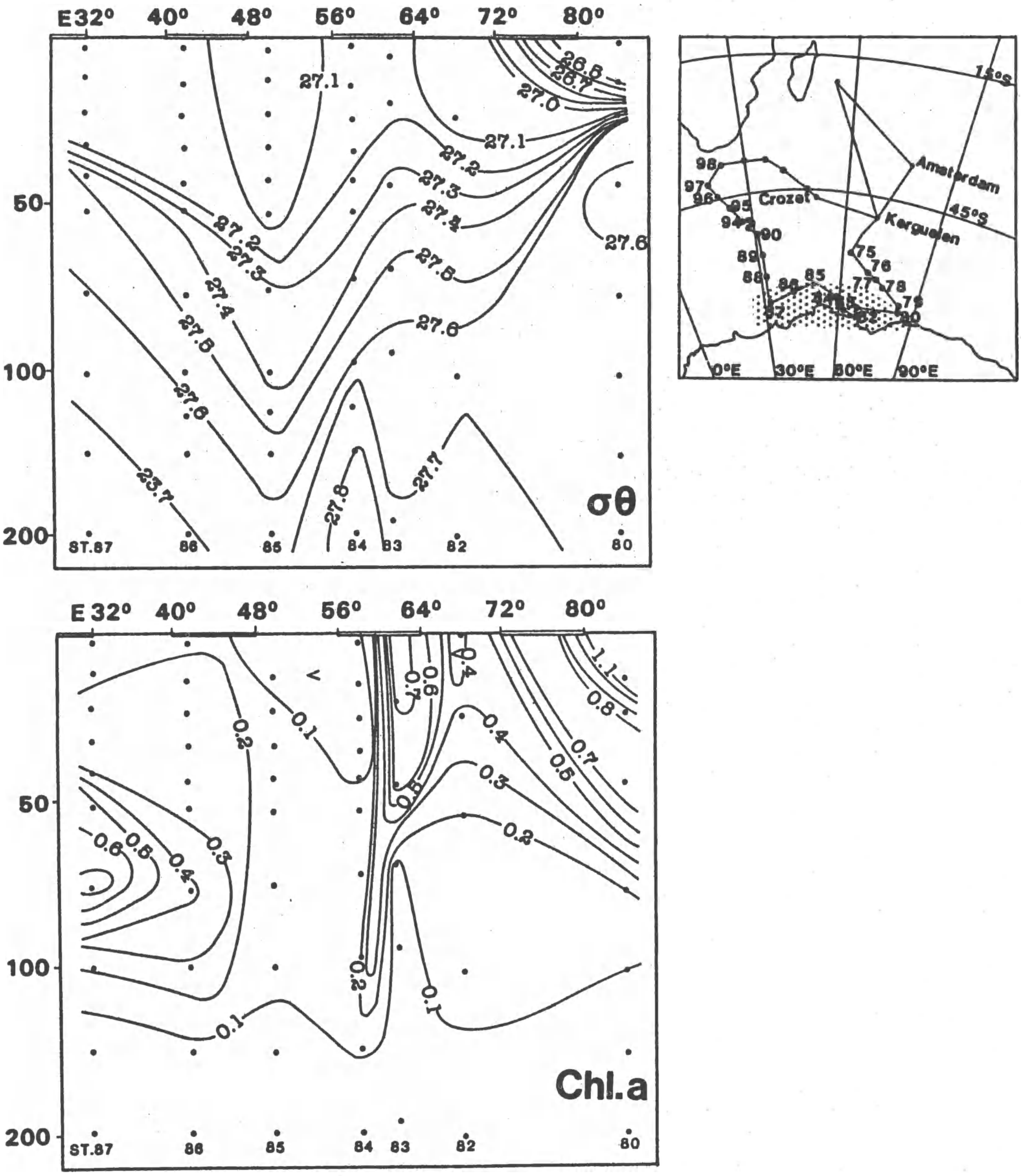

Fig.7B: Vertical distribution of density (σ_θ) and chlorophyll-a concentration (mg chl.a/m^3) from the surface to 200 meters deep along the southern track (Stations 87 to 80). Density has been calculated from temperature and salinity data of A.Poisson's INDIGO III research team.

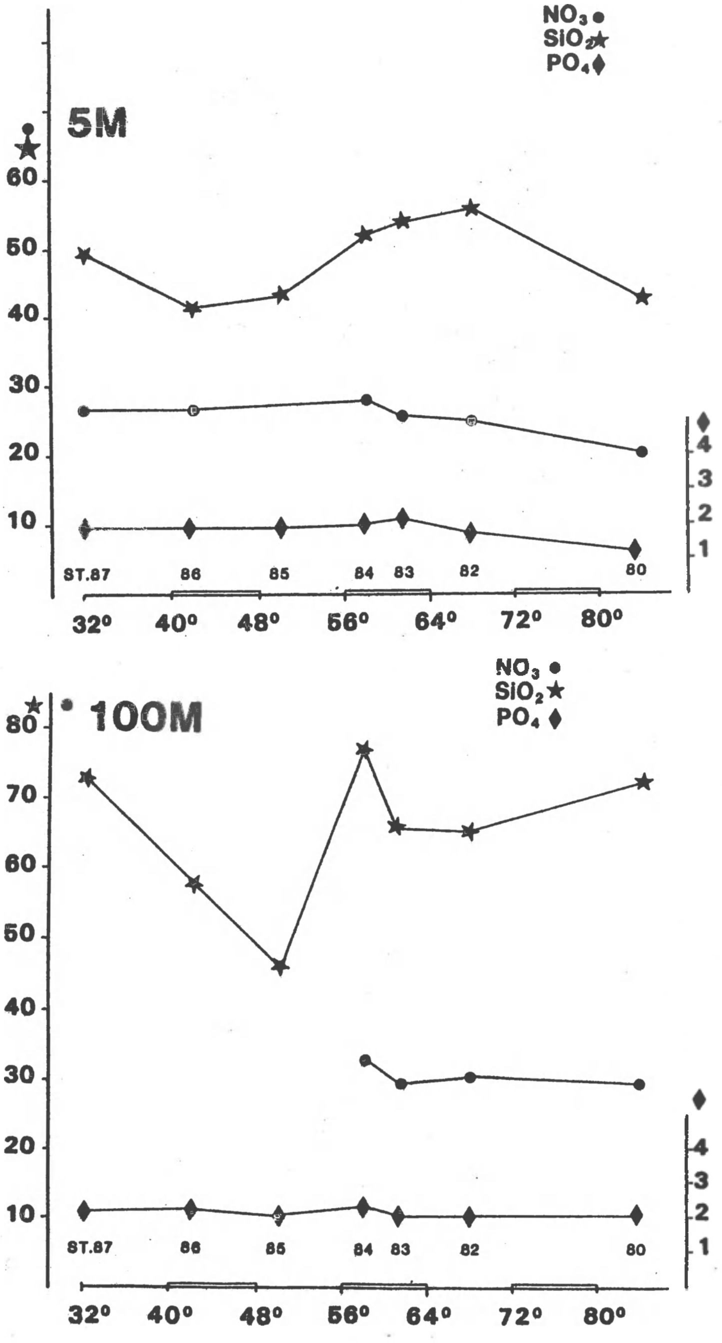

Fig.8: Horizontal distribution of reactive phosphate, silicate and nitrate at the sea-surface and at 100 meters deep (μgat/l) along the southern track (Stations 87 to 80). Data obtained from A.Poisson's INDIGO III research team (PO_4 and SiO_2) and F.Dehairs and L.Goeyens (NO_3).

DISCUSSION

Data obtained during Indigo III cruise show again that wide geographical variation of chlorophyll-a standing crops in the Southern Ocean is common.
They confirm that frontal systems do not act only as physical boundaries but they, themselves may be areas of enhanced biological activity.

Between South Africa and Antarctica, the geographical location of the main frontal systems has been established with a great degree of confidence, referring to many authors.
Results from the horizontal sea-surface track confirm patterns of phytoplankton distribution reported by Planke (1977), Jacques et Minas (1981) and Lutjeharms et al(1985).
At the sea-surface, the two major peaks in chlorophyll-a concentration, occuring at the Subtropical Convergence and at the Antarctic Polar Front, are associated with the frontal systems who have the characteristics of a convergence.
According to Planke (1977) and Lutjeharms et al.(1985) , the Subtropical Convergence south of Africa is characterized by a "dramatic dynamic variability". So, the peak observed north of the gradient could be associated with cross-frontal eddies moving northwards.
Phytoplankton increase around 60°S has often been observed during summer (Jacques et Minas,1981; Lutjeharms et al.,1985) and seems to occur only in the area where surface warming increases the stability of the water column significantly (Lutjeharms et al.,1985).

The vertical phytoplankton distribution, shown between surface and 200 meters deep, must be carefully interpreted, because of stations removal, especially in the frontal areas.
However, despite this, phytoplankton accumulations seem to be strongly correlated with the surface and subsurface expressions of the main frontal systems. High phytoplankton biomasses (0.5 - 1.5 mg chl.a/m^3) are observed close to the density gradients and more than 0.5 mg chl.a/m^3 are found till a depth of 70 meters (85 for the Antarctic Divergence).

On the other side, in interfrontal areas, phytoplankton is always situated in the upper layers of the water column. There, in spite of high nutrients disponibility, chorophyll-a concentration is very low (0.1 - 0.3 mg chl.a/m^3), except for the above discussed western track's zone around 60°S.

In the frontal areas of the Southern Ocean, the high living chlorophyll-a standing crops observed between surface and 70 meters deep suggest a downwards transport of phytoplankton along the strongly sloping isopycnals in relation with vertical currents associated with the frontal hydrodynamics.
At an other spatial scale, at the Liguro-Provençal Front (Mediterranean Sea), Hecq _et al._(1986) have shown that phytoplankton biomass increases accross the density gradient and that living chlorophyll-a, produced at the sea-surface, is carried along the isopycnals, in relation with the frontal convergence.
A similar mechanism should exist in the Southern Ocean but a more intensive and detailled study of the antarctic frontal systems (continuous measurements, frequent vertical sampling, meteorological data acquisition) is essential to have a better understanding of the phytoplankton distribution and productivity.

Our aim for the next cruises is to obtain a representative picture of frontal effects on phytoplankton characteristics and to work out, in these particular areas, phytoplanktonic biomass enhancement and his availability for ecosystem.

CONCLUSIONS

Preliminary results obtained in the Southern Ocean during Indigo III cruise confirm the alternative occurences of larger and smaller chlorophyll-a stocks reported by many previous authors.

Highest chlorophyll-a standing crops are associated with the main frontal systems (the Subtropical Convergence, the Antarctic Polar Front and the Antarctic Divergence).
In these particular areas, significant amounts of living phytoplankton are found as far as 70 meters deep, suggesting a downwards transport of chlorophyll-a along isopycnals, in relation

with the frontal hydrodynamics.
In interfrontal areas, chlorophyll-a concentrations are generally very low and restricted to the upper layers of the water column. Therefore, the vertical distribution of phytoplankton in the Southern Ocean is not as uniform as expected, referring to El Sayed (1978) or to Jacques et Minas (1981).

These preliminar results show that a more intensive and detailed study of the antarctic frontal systems might lead to a better understanding of the phytoplankton distribution and productivity.

ACKNOWLEDGEMENTS

The authors are indebted to Dr.A.Poisson from LPCM (Paris IV) for his invitation to participate in Indigo III cruise. They are grateful to the TAAF (Terres Australes et Antarctiques Françaises) and to the crewmembers of the R.V."Marion Dufresne" for their welcome and logistic support. This text presents results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsibility is assumed by its authors. Dr.J.H.Hecq is research Associate of the Fonds National Belge de la Recherche Scientifique.

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FREEZING RATE DETERMINATION BY THE ISOTOPIC COMPOSITION OF THE ICE : IMPLICATIONS IN ANTARCTIC STUDIES

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Freezing rate and isotopic composition

KEYWORDS : freezing rate - isotopic composition - ice.

ABSTRACT

Development of a box diffusion model combined with the boundary layer concept leads to a possibility of determining freezing rates from the isotopic composition of the ice. The model is tested experimentally and first field results are given. Implications for antarctic glaciology are outlined : determination of sea ice growth rate, of accretion rate at the base of ice shelves and of basal ice rate of formation.

INTRODUCTION

Recently, it has been shown that samples of ice due to the freezing of water are aligned in a δD-$\delta^{18}O$ diagram on a characteristic freezing slope that does not vary with the freezing rate (Jouzel and Souchez, 1982 ; Souchez and Jouzel, 1984). However, the distribution of points representing different percentages of freezing on this slope is dependent on the freezing rate. The δ unit denoted hereafter is the relative range of the isotopic ratio in the sample versus the same ratio in S.M.O.W. (standard mean ocean water) and expressed in per mil.

METHODS

Distribution of a heavy isotopic species in ice during water freezing is related to the distribution in the liquid immediately adjacent to the freezing front. Since diffusion in the ice is slow ($\approx 10^{-11}$ cm^2 sec^{-1}), the distribution produced in the ice can be obtained from knowledge of the variations in the liquid at the interface. These variations depend on mixing that occurs by diffusion and by convection.

If mixing is sufficiently strong to maintain an uniform concentration throughout the water at all times during freezing, a Rayleigh distribution (Dansgaard, 1964) in the ice is obtained, in which $(1+\delta_S) = \alpha(1+\delta_O)f^{\alpha-1}$ where $1+\delta_S = R_S$ is the isotopic ratio in ice, $1+\delta_O = R_O$ the isotopic ratio in the initial water, f the remaining liquid fraction and α the equilibrium fractionation coefficient (Fig. 1). This situation occurs for very low freezing rates.

Another limiting case is that in which transport in water occurs by diffusion only. Ice has an initial isotopic ratio $R_S = \alpha R_O$. Thus, water at the interface is depleted in the heavy isotope and a concentration gradient is established. Diffusion of the heavy isotope will occur from the main body of water. A steady-state may occur in which the input into the diffusion layer is equal to the output into the ice (Fig. 1). The initial transient is the region in which the isotopic ratio in ice falls from its initial value of αR_O to the steady-state R_O. A terminal transient occurs when the ice-water interface approaches the end of the reservoir so that the diffusion necessary to maintain steady-state freezing is no longer possible.

Although mixing can be achieved throughout the bulk of the liquid, a zone in which transport takes place by diffusion only, always exists adjacent to the ice-water interface, as a boundary layer of thickness BLT. Because of the existence of this boundary layer, the uniform concentration throughout all the water is not attained, and this will affect the distribution in ice. The thickness of this boundary layer depends upon the amount of mixing present in the liquid.

Modelling of the redistribution of isotopic species during water freezing is mathematically equivalent to the modelling of the redistribution of a solute during solidification, a problem extensively studied for preparation of materials by zone melting. For the one dimensional case in which growth proceeds by the movement of a plane interface separating liquid and solid, and, in the absence of convection, this problem has been solved analytically (Tiller et al., 1953; Smith et al., 1955). If a boundary layer is introduced, such an approach is quite complex, particularly if the freezing rate varies during the freezing phase. We develop a numerical approach using a simple box diffusion model, introducing the constraint that pure diffusion is limited to the boundary layer and considering that

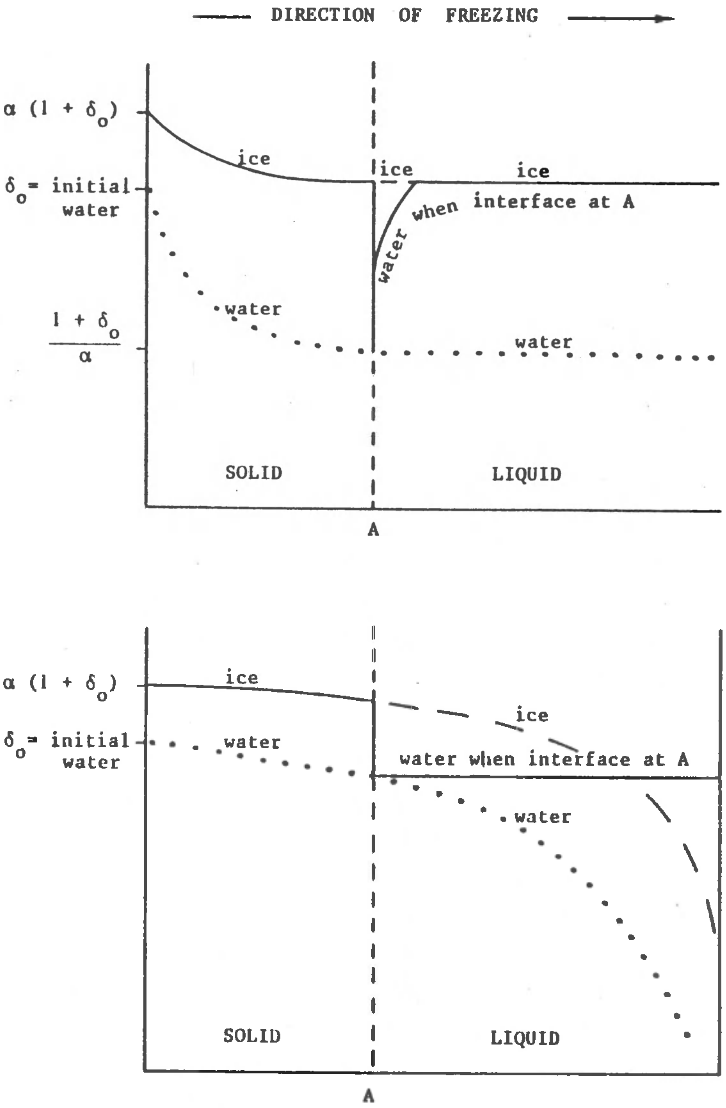

Fig. 1. Isotopic distribution in ice and water in the course of freezing.

Top : development of a steady state when transport in water occurs by diffusion only.

Bottom : development of a Rayleigh distribution when mixing is sufficiently strong to maintain an uniform concentration throughout the water.

complete mixing, i.e. water homogenization, occurs in the remaining part of the reservoir (Souchez et al, 1987).

The numerical model consists of two successive stages : for each box that freezes, computation of the isotopic ratio of the first adjacent liquid box is made ; then a certain number of diffusion steps are programmed, depending on the freezing rate. A diffusion step consists in the application of Fick's law of diffusion from one box to another, for all the liquid boxes. If the δD value of the box at the outer limit of the boundary layer is modified by the diffusion steps considered, a new mean identical δD value is calculated for all the remaining boxes to take into account the complete mixing in the remaining part of the reservoir. A specific boundary layer thickness (BLT) is thus considered for each simulation.

Only the isotopic ratio D/H is considered here, so that the equilibrium fractionation coefficient α is 1.0208 (Arnason, 1969). A similar procedure can be done for oxygen.

Results of the computing with different values of BLT, for a given freezing rate of 5 mm h^{-1} and a total length L of 10 cm, are shown on Figure 2a. If BLT = 0, a Rayleigh distribution with the equilibrium fractionation coefficient α is displayed. For BLT ≥1 cm, the curve is identical to the one obtained by a simple diffusion process (no convection) and exhibits a steady-state after an initial transient. For lower values of BLT, a part of this initial transient exists, followed by a Rayleigh-type distribution with an apparent fractionation coefficient different from the equilibrium value. The part of the initial transient common for all the curves is very well approximated by :

$$\delta_S = \delta_O + (1 + \delta_O)(\alpha - 1)\, e^{\frac{-\alpha V x}{D}}$$

where x is the frozen thickness. Thus, the freezing rate can be determined by knowing the distance of the sample from the freezing front at the beginning of freezing and the isotopic composition of the ice.

Freezing rates are usually dependent on the thickness of the ice already formed, i.e. the position of the interface at

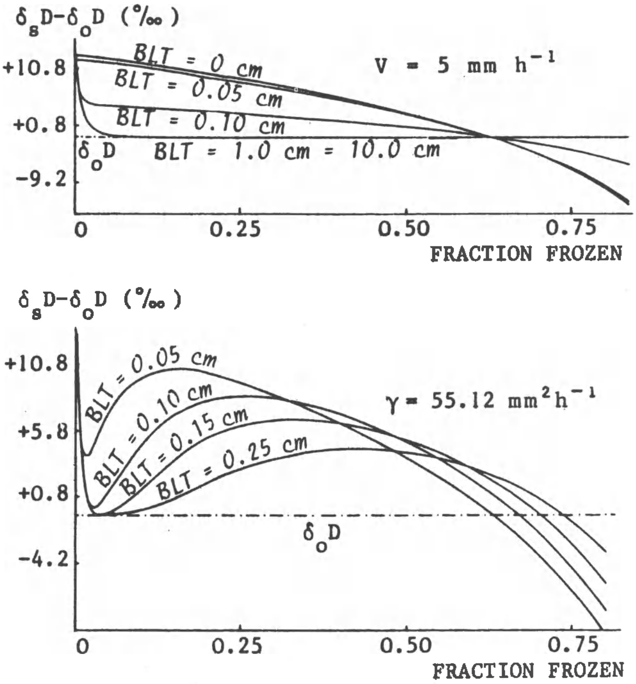

Fig. 2. Influence of the boundary layer thickness (BLT) on the isotopic distribution in ice.

Top : for a given constant freezing rate

Bottom : for a decreasing freezing rate with a given γ value.

$\delta_s D-\delta_o D$ is the difference between the δ value in the ice and the δ value of the initial water.

time T. Applying heat transfer theory and experimental work, Terwilliger and Dizio (1970) found that the freezing rate is related to the increase of the interface position by :

$$V = \frac{\Delta x}{\Delta T} = \frac{\gamma}{x}$$

They thus consider an hyperbolic decrease of the freezing rate in relation to the interface position x, the constant γ characterizing this evolution.

Introducing varying freezing rates in our model, a δD distribution curve in ice is obtained for given γ and BLT values (Figure 2b). This curve shows an initial drop, a minimum and a reverse gradient before the Rayleigh-type decrease. For increasing values of BLT, the position of the minimum is changed and the reverse gradient decreases. For a given reservoir, once the position of the minimum and the value of the reverse gradient are determined, γ and BLT are known.

RESULTS

The model has been experimentally tested. Three unidirectional freezing experiments, using a cryostat, have been conducted in a cylinder of 10 cm length and 8 cm diameter with meltwater from different antarctic ice cores from Plateau Station and Roi Baudouin Station. Interface positions in the course of time were measured for each freezing experiment ; results show a linear relationship between the interface position and the square root of time in accordance with heat transfer models (Terwilliger and Dizio, 1970). From this, the hyperbolic decrease of the freezing rate can be calculated. Taking this decrease into account in the simulations of the model with the appropriate initial water values, a theoretical δD distribution curve in ice can be obtained. Figure 3 shows this curve for each experiment in solid lines.

The ice cylinder obtained in each experiment was sliced in a cold room using a microtome device. Results of the isotopic analyses in δD are plotted on Figure 3 as black dots. In the three experiments, the minimum and the reverse gradient are observed and, for PS1, where more values were obtained at the onset of freezing, the initial drop is displayed.

A close agreement exists between model and experiment indicating a possible use of the theory for determining freezing rates in nature.

The model has also been tested against lake ice and the results are in fair agreement with what you would expect : the two cold waves detected by the isotopic distribution were registered in the meteorological records of the site. Further developments can be found in Souchez et al (1987).

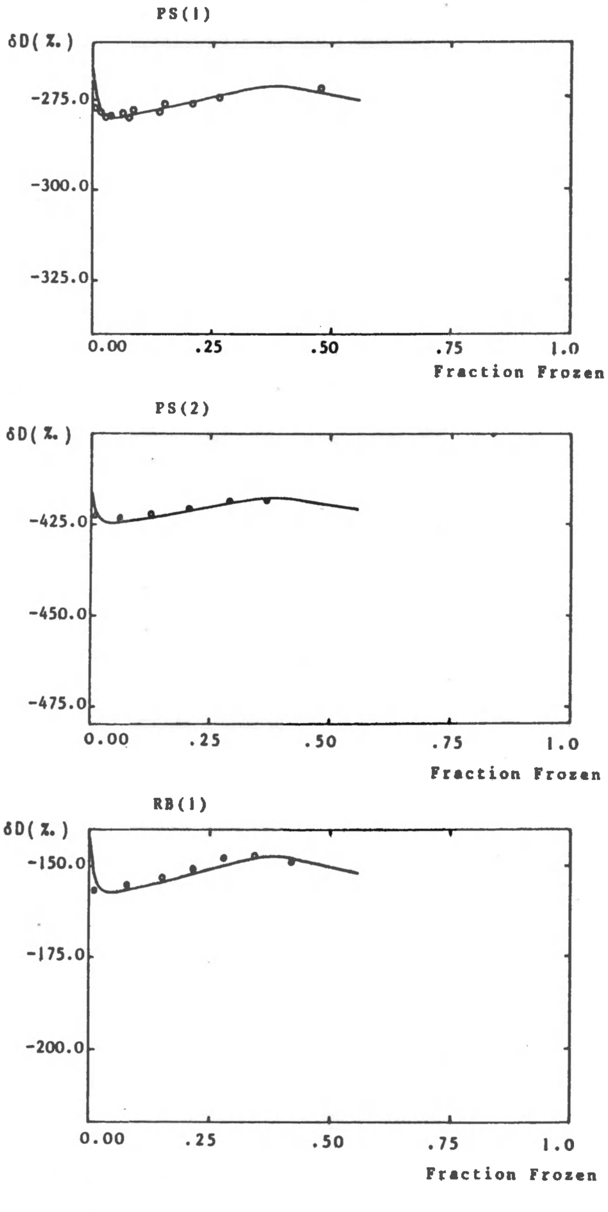

Fig. 3. Theoretical curve (solid line) and experimental results (black dots) for the δD distribution in ice in the three experiments.

Freezing rate and isotopic composition

Sea ice formed during the austral winter 1986 was sampled in Breidbay near the antarctic Japanese station Syowa by Dr. H. Decleir and transfered frozen to our cold room. Results of isotopic measurements are still in progress but are very encouraging. No doubt that a freezing rates history can be deduced from a joint investigation of the isotopic distribution in δD and the crystal size determination. Different minima in the isotopic distribution are displayed, less and less developed as one proceeds down the core. This is in connection with the damping of cold waves as sea ice grows.

Determination of freezing rate by the composition in stable isotopes of the ice implies the achievement of an isotopic profile with great precision. This is actually possible since the deuterium content of an ice sample can be measured with an accuracy of 0.5 ‰ on very small volumes (0.3 ml).

CONCLUSION

The three following applications are possible in the Antarctic :

a) evaluation of the rate of sea ice growth where the ice cover is mainly congelation ice rather than frazil ice. This is the case along the border of the antarctic continent. Such an approach would have climatological and ecological implications.

b) determination of the accretion rate at the base of antarctic ice shelves by freezing of sea water. This kind of study has some implications in mass balance studies.

c) investigations of basal ice rate of formation in deep antarctic ice cores.

Since freezing rates and sliding rates are connected to some extent at the glacier base in the pressure melting-regelation process, information on freezing rates can produce a refinement of ice-sheet flow models that are needed for a paleoclimatic interpretation of deep ice cores.

ACKNOWLEDGEMENTS

Prof. H. Decleir and M. Devos, from Vrije Universiteit Brussel, are gratefully acknowledged for collecting the sea ice cores. The authors would also like to thank the National Institute of Polar Research, Japan for their efficiency in taking care of the samples to Tokyo airport and M. Depasse from the Belgian embassy in Tokyo for his cooperation.

This paper is a contribution to the Belgian scientific program on Antarctica (Science policy office). The scientific responsibility is assumed by its authors.

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2D SIMULATION OF WEDDELL SEA CIRCULATION

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

2D SIMULATION OF WEDDELL SEA CIRCULATION

KEYWORDS
2D model, tidal circulation, Weddell Sea, ADI scheme,

ABSTRACT

The circulation in the Weddell Sea is simulated by means of a 2D numerical model which solves the depth-averaged St. Venant equations. An appropriate application of these equations makes it possible to calculate surface currents for shelf area and for the deep sea as well. The St. Venant equations are integrated numerically by a finite difference method using an alternating direction implicit (ADI) scheme with the splitting-up of the continuity equation. This gives rise to a very efficient computer implementation. All the calculations can be carried out on a personal computer PC-AT and take about 15 min for a full tidal cycle. The model can thus serve for operational, i.e. real time purposes.

Results are presented for wind-driven and tidal-induced circulations. The wind pattern is obtained by using mean monthly data (Taljaard et al., 1969). The tidal circulation is calculated by open boundary forcing (8 tidal components) obtained from global ocean tidal simulations (E.W. Schwiderski, 1983). The calculations show a qualitively good result compared with observed features of the Weddell Sea circulation. The circumpolar current and the high flow velocities in the Drake passage are satisfactorily reproduced.

1. INTRODUCTION

Icefields can be fragmented under the influence of currents and wind, locally ice-ridges or ice-free zones can be formed. Ice is inconvenient for navigation : navigation routes can be blocked by icefloes, ships can get stuck in the pack-ice with possibly disastrous consequences for ship and crew.

The prediction of ice condition is possible by means of a model. As input the model requires predicted wind data; these data will be utilized to calculate the ocean currents and the ice concentration.

The aim of this research is to develop a numerical flow model for the Weddell Sea. The knowledge of ocean currents is necessary to predict the seasonal evolution of the icefields. The ocean model will be coupled to an ice model, developed at the BMM/UGMM, (Demuth and Van Ypersele, 1987). The following themes are presented in the paper :

- the presentation of an efficient and accurate algorithm for steady and unsteady flow problems;
- the application of the model for the Weddell Sea for tidal flow and wind driven circulation.

2. CHOICE OF THE MODEL

A numerical flow model consists of a set of partial differential equations, i.e. the conservation equations for mass and momentum describing the hydrodynamics of the flow, of boundary and initial conditions and of some parameters, such as the Chézy coefficient, which have to be determined empirically. The choice of the model is suggested by the following items :

a) The aim of the model.
   A good choice must be made in function of the desired results.
   The thickness of an layer of ice is small, the dynamics of it is particularly influenced by surface currents - a 2D phenomenon. The restriction to a 2D model is obtained by integrating the 3D equations over the depth.

b) Solution techniques.
   An analytical solution for the differential equations exists for some simplified cases; usually, numerical solution techniques are applied. The choice of the numerical scheme determines the accuracy of the solution and the efficiency of the computer implementation (computing time, memory space, computer cost). Three-dimensional models need a lot of computing time and memory space, therefore, they can only be implemented on a big computer. These models are not suitable for short term predictions and, moreover, difficult to calibrate for lack of measurements in three dimensions. A two-dimensional model, on the other hand, need less computing time and relatively little memory space. When choosing an efficient numerical scheme such a model can run on a personal computer.

With this in mind a 2D depth-averaged model has been chosen :

- the phenomena of interest are essentially two-dimensional (surface currents, ice dynamics);
- the computing time is small; therefore, real-time (operational) applications, such as navigation guidance, are possible.

The numerical scheme of the model uses an "alternating direction implicit" (ADI) algorithm with the splitting-up of the continuity equation. The ADI procedure applies a "double sweep" method for the efficient solution of the equations. The numerical scheme is unconditionally stable, the choice of the timestep and the grid distance depends only on the accuracy desired.

3. DYNAMIC EQUATIONS

The equations which are solved by the model are the shallow water equations (St. Venant hypothesis). The advective terms are neglected as they are of less importance for the simulation of the currents for the Weddell Sea. The equations of horizontal flow motion can be written as

$$\frac{\partial u}{\partial t} + g\frac{\partial Z}{\partial x} - f.v + R\sqrt{u^2 + v^2}\,.\,u + \frac{1}{\rho}W_x = 0 \qquad (1)$$

$$\frac{\partial v}{\partial t} + g\frac{\partial Z}{\partial y} + f.u + R\sqrt{u^2 + v^2}\,.\,v + \frac{1}{\rho}W_y = 0 \qquad (2)$$

and the conservation equation for mass as

$$\frac{\partial Z}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0 \qquad (3)$$

where the notation is as follows :

x,y	x and y co-ordinates
t	time
H	total water depth
z	water-level elevation relative to the reference plane
u,v	vertically averaged velocity components in the x and y co-ordinate direction
f	Coriolis' parameter
ρ	fluid density

g gravitational acceleration

R is expressed as

$$R = \frac{g}{C^2 H} \tag{4}$$

where C is the Chézy friction coefficient.

$$W_x = \lambda_{\rho a} W_u \sqrt{W_u^2 + W_v^2} \tag{5. a}$$

and

$$W_y = \lambda_{\rho a} W_v \sqrt{W_u^2 + W_v^2} \tag{5. b}$$

are the wind-stress components in x and y directions respectively, and W_u and W_v are local wind velocity components in x and y directions, ρ_a is the air density and λ the drag coefficient at the air-water interface.

Depth-averaged models have been widely applied for about 30 years for tidal and stormsurge prediction and for the simulation of transport phenomena, (Hansen, 1956; Sündermann, 1966; Leendertse, 1970; Abbott et al., 1972; Dronkers, 1975; Weare, 1976; Moelans, 1979; Benqué et al., 1982; Vreugdenhil and Wijbenga, 1982; Stelling, 1984; Smith and Cheng, 1987 etc).

These models have been mostly used for the simulation of continental shelf seas. In the present paper it is shown that they are also suitable for the simulation of surface currents outside the shelf area. Martinsen et al. (1979) developed a model for the west coast of Norway, the area is partly situated outside the continental shelf. They used an idealized bathymetry. The model of the Weddell Sea has no a realistic bathymetry. The water depth is reduced. This means that the "bottom" of the model lies in the water. The value of the bottom friction must, therefore, be low. This approach is permitted as the surface layer of the ocean differs from the underlying layer and the momentum exchange between the surface layer and the lower layer is small. According to vertical velocity profiles from the 3D model of van Ypersele de Strihou (1986) the depth of the model was put at 100 m. This corresponds to the depth of the photic layer.

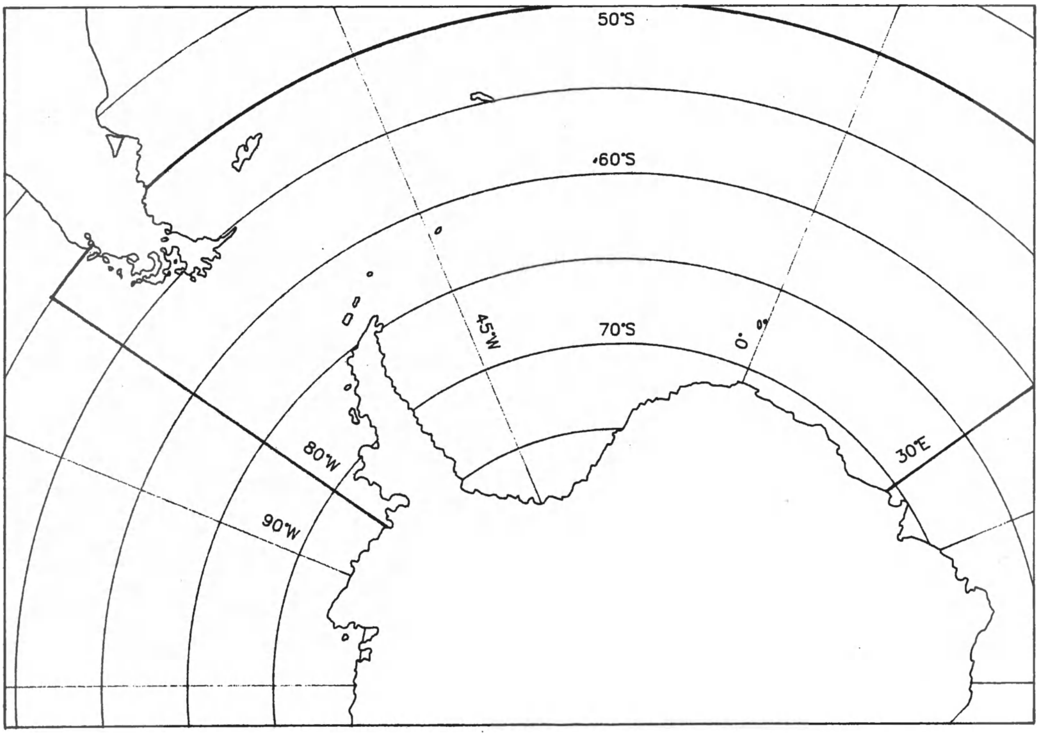

Fig. 1. Model area.

4. FINITE DIFFERENCE MODEL

The set of equations (1) to (3) is not solved at every time step. The following procedure, for example, was pursued by Liu and Leendertse (1978) : At every time step only one of the conservation equations of momentum (1) or (2), together with the continuity equation (3), is solved implicitly. The remaining equation is solved explicitly. A fully implicit formulation is necessary to make the scheme unconditionally stable. The continuity equation is, therefore, split into two falsified equations :

$$\frac{1}{2} \cdot \frac{\partial Z}{\partial t} + \frac{\partial (Hu)}{\partial x} = 0 \text{ for odd time-steps} \qquad (6)$$

and

$$\frac{1}{2} \cdot \frac{\partial Z}{\partial t} + \frac{\partial (Hv)}{\partial y} = 0 \text{ for even time-steps} \qquad (7)$$

The individual stages (6) and (7) are not consistent with the original equation (3), but the resultant of two stages is (Yanenko, 1971). During one computational cycle, two successive time levels were executed in the following order : (1) and (6) were solved in x direction at odd time-steps, similarly (2) and (7) were solved in y direction at even time steps. The scheme is completely centered in derivatives, which avoids non-linear instabilities (Yanenko, 1971; Yu et al., 1988). A detailed description of the finite difference equations and the implementation on computer was given in Moelans and De Bruyn (1986).

5. MODEL AREA

The coast-lines of the region are represented by a 111 x 111 km^2 horizontal grid. The boundaries of the model are situated at 50°S and 80°S latitude and 80°W and 30°E longitude, including the Antarctic peninsula, the southern tip of South America and the Drake passage (see Fig. 1 and Fig. 2).

The area contains a few islands, which because of the implicit formulation of the model, can easily and without loss of efficiency be incorporated in the model. The geometry is taken from the Admiralty Charts Nos 3170, 3175, 3176 and 3200.

6. RESULTS

In this chapter the results will be discussed obtained from the calculations of the currents due to wind action of those due to tidal action and of those due to a combination of both.

For the calculations the model needs boundary and initial conditions.

The treatment of the open boundary is an intrinsic and important problem associated with hydrodynamic numerical (HN) models. In limited area modelling there is a difficulty in prescribing lateral boundaries since no true physical boundaries exist. Three ways of approach are discussed in this chapter.

The first is a kind of extrapolation method : the boundary is specified by extrapolating the solution at the interior points to the boundary (6.1.1.).

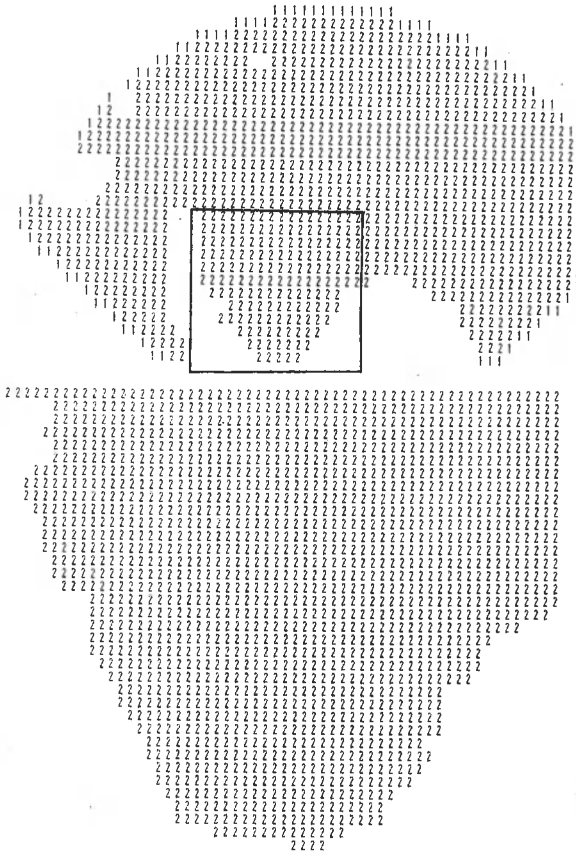

Fig. 2. (a) Coarse grid, (b) Fine grid.

The second is the so-called grid nesting : the boundaries are put far away from the region of interest and the coarse grid will serve to generate a boundary condition for the fine grid (6.1.2.).

The third consist in the use of a surface elevation boundary to calculate the tidal circulation. This method is applicable to vertically-integrated models, (Butler and Cheng, 1984).

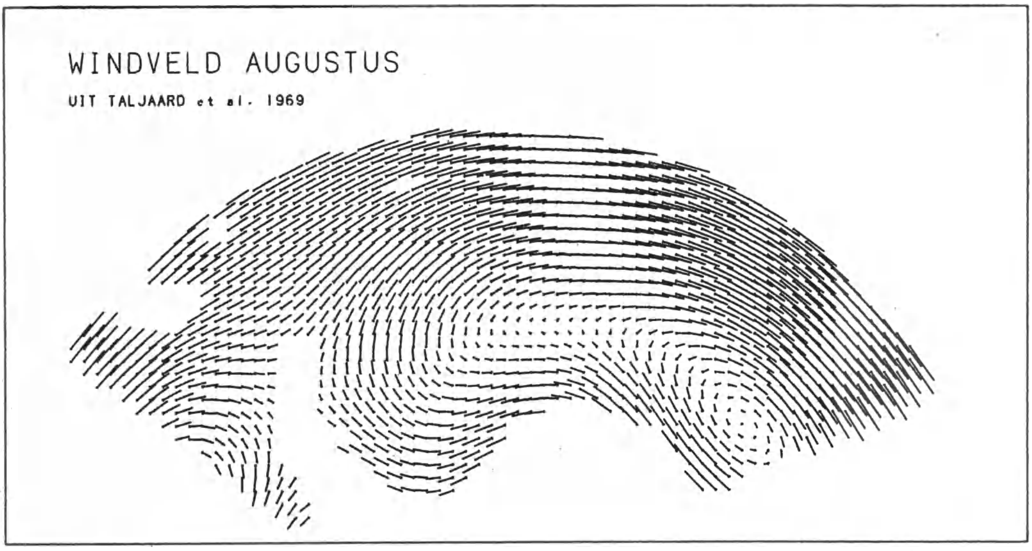

Fig. 3. Averaged windfield of August, from Taljaard et al. (1969).

6.1. Currents due to wind action

The wind is the most important flow forcing component for the permanent currents around Antarctica. The main direction of the wind is from the west. Near the coast the wind blows from an opposite direction (see Fig. 3).The wind data were taken from Taljaard et al. (1969). The currents are typically circumpolar, the so-called Antarctic circumpolar currents. The main directions of the currents are analogous to the wind directions.

6.1.1. Extrapolation boundary condition method

Because of the circumpolar nature of the currents in Antarctica the eastern and the western boundaries were connected in such a way that the water flowing out at the western boundary enters again at the eastern boundary and vice

versa. The northern boundary is closed. This method was applied by van Ypersele de Strihou (1986).
It leads, however, to numerical instabilities when applied to the model presented here, probably because of the required extrapolation, (Chen, 1973). Notwithstanding this fact, the features of the Antarctic currents are well simulated : the stronger flow in the northern part, the higher velocities in the Drake passage, the westward currents near the coast and the Weddell sea gyre are reproduced, (see Fig. 4.)

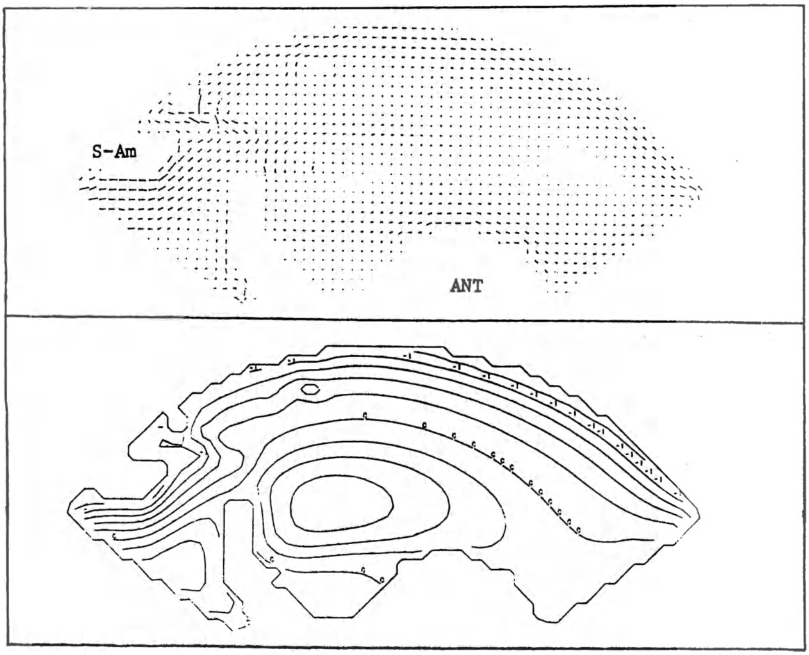

Fig. 4. Extrapolation boundary condition (a) current vectors, (b) isolines of waterelevation.

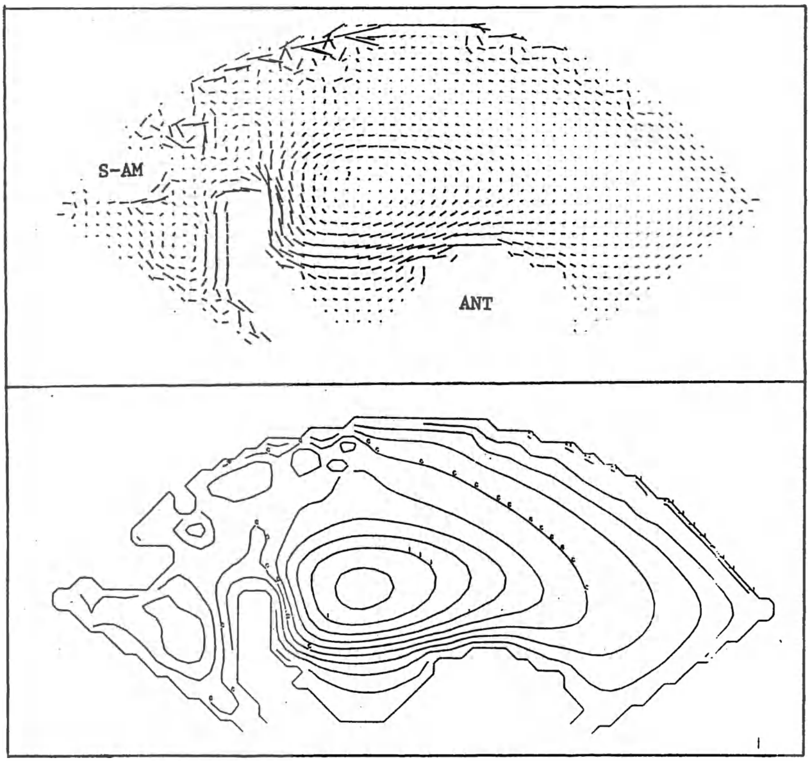

Fig. 5. Closed boundary conditions. (a) current vectors. (b) isolines of waterelevation.

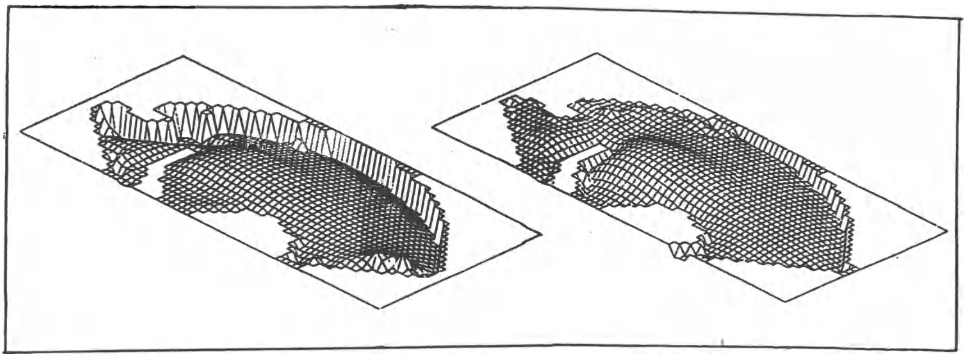

Fig. 6. Waterelevation for model with (a) extrapolation boundary condition and (b) closed boundary condition.

6.1.2. Closed boundary condition method

For this simulation, in addition to the northern boundary, also the eastern and western open boundaries have been assumed to be closed, i.e. they have been considered continental boundaries. No problems with numerical instabilities of the scheme appear. The comparison of the results of Fig. 5 with those of Fig. 4, shows that the flow field close to the boundaries is distorted, but in the central part of the area, i.e. in the area of interest, it is at least qualitatively good. The coarse grid acts as a damper of the errors due to a physically incorrect boundary specification and it is needed to generate a realistic boundary condition for the fine grid. A disadvantage of such an approach is that the area gets bigger and the number of computational points is higher. Because of the high performance of the numerical scheme and the efficient implementation of the fine grid, this is only a minor restriction, (Moelans and De Bruyn, 1986; Yu <u>et al</u>., 1988).

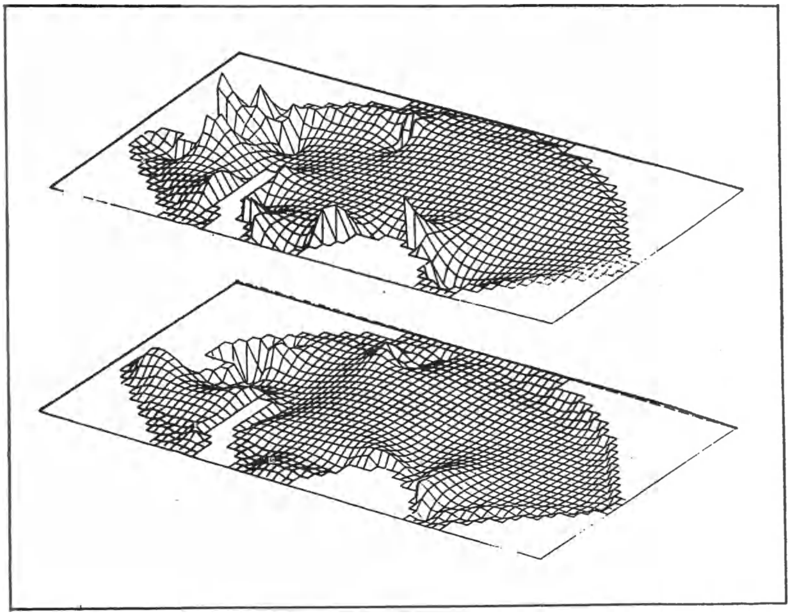

Fig. 7. Simulation of M2 tide : waterelevation. (a) at 0h00min. (b) at 7h50min.

6.2. Currents due to tidal forcing

The Weddell Sea is an area which is subject to rather large tides, as compared with the ocean. In the development of a model suitable as a navigation guide the knowledge of the tidal circulation is very important. Observational data on tides in the Southern Ocean are scarce. The boundary data necessary for implementing the tidal boundary are therefore obtained from the global ocean tidal simulation, calculated by Schwiderski (1983). In Fig. 7 the results are presented for the M2 tidal constituent, calculated with the Weddell Sea model. The maximum tides are situated in the Weddell Sea and on the continental shelf zone of South America, this is in agreement with observations and with the results of Schwiderski's model (1983). Fig. 8 provides the result of an simulation with the O1-constituent only. In Fig. 9 and Fig. 10 a simulation is done for 9 constituents (Q1, O1, P1, K1, N2, M2, S2, K2, Mf).

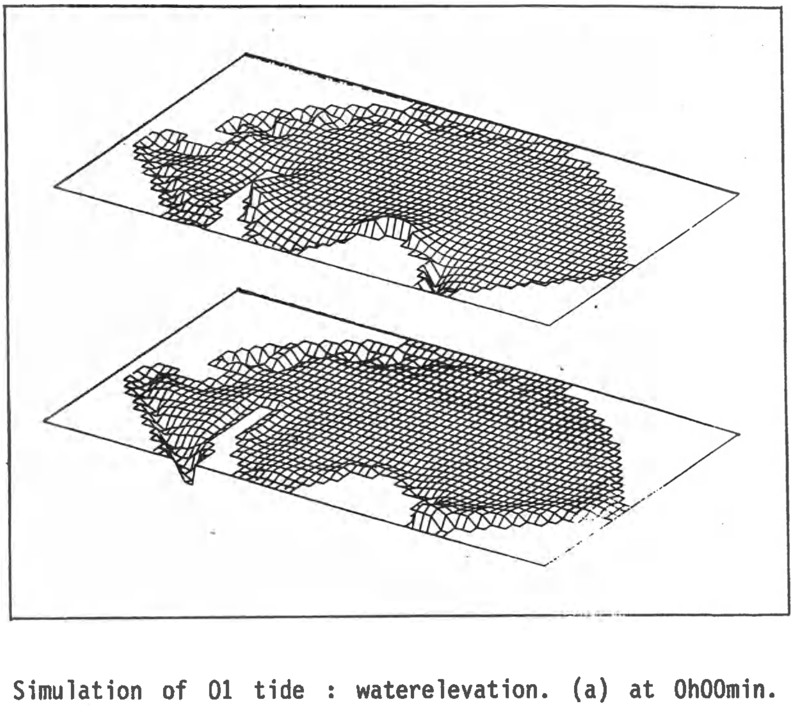

Fig. 8. Simulation of O1 tide : waterelevation. (a) at 0h00min. (b) at 7h50min.

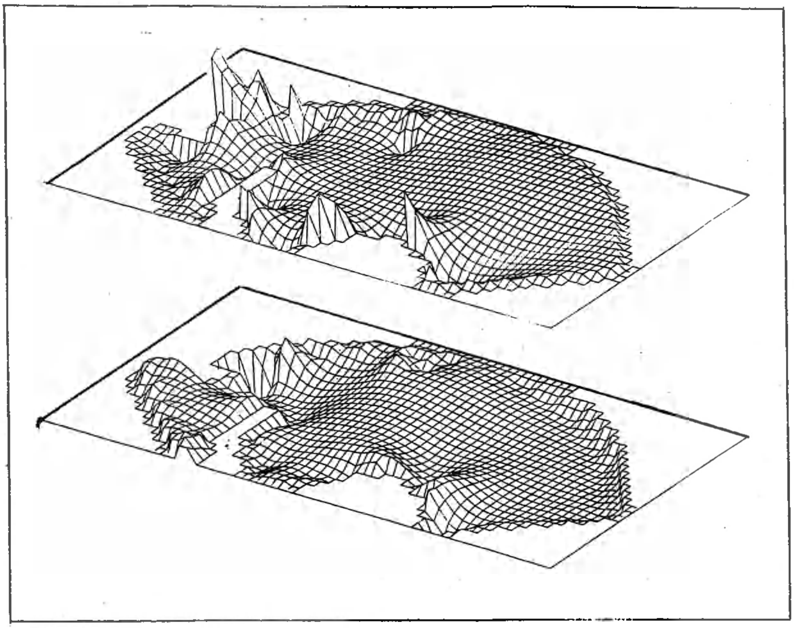

Fig. 9. Simulation of the tides (9 constituents) : waterelevation (a) at 0h00min. (b) at 7h50min.

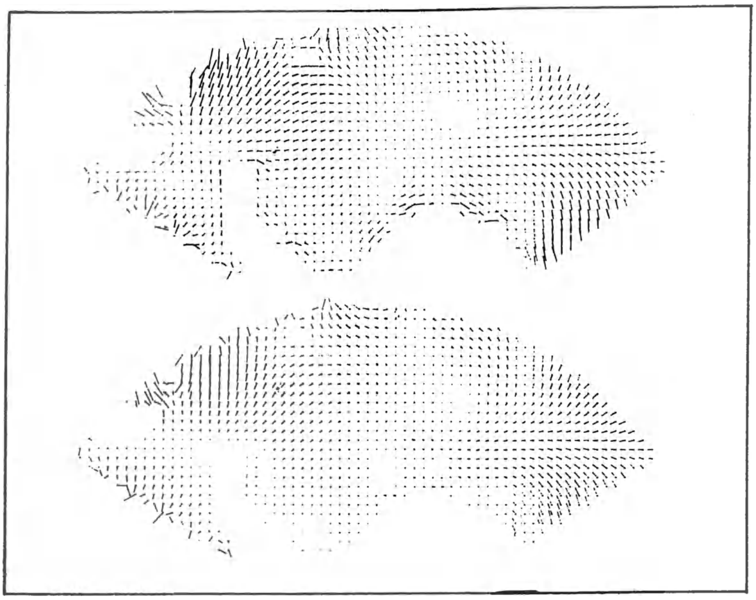

Fig.10. Simulation of the tides (9 constituents) : current vectors. (a) at 0h00min. (b) at 7h50min.

6.3. Currents due to wind and tidal action

In the previous chapters computations have been carried out in order to simulate the response of the Weddell Sea to wind stress alone and to tidal action respectively. In this chapter some preliminary results of "wind and tide combined" are presented. The results of "wind alone", "tide alone" and the combination will facilitate the study of tide-surge interaction. In Fig. 11 a comparison is made between the water elevation due to tidal action, and that due to tidal and wind action combined. The wind effect is small, because the wind velocities are small near the coast and the wind stresses are monthly averaged.

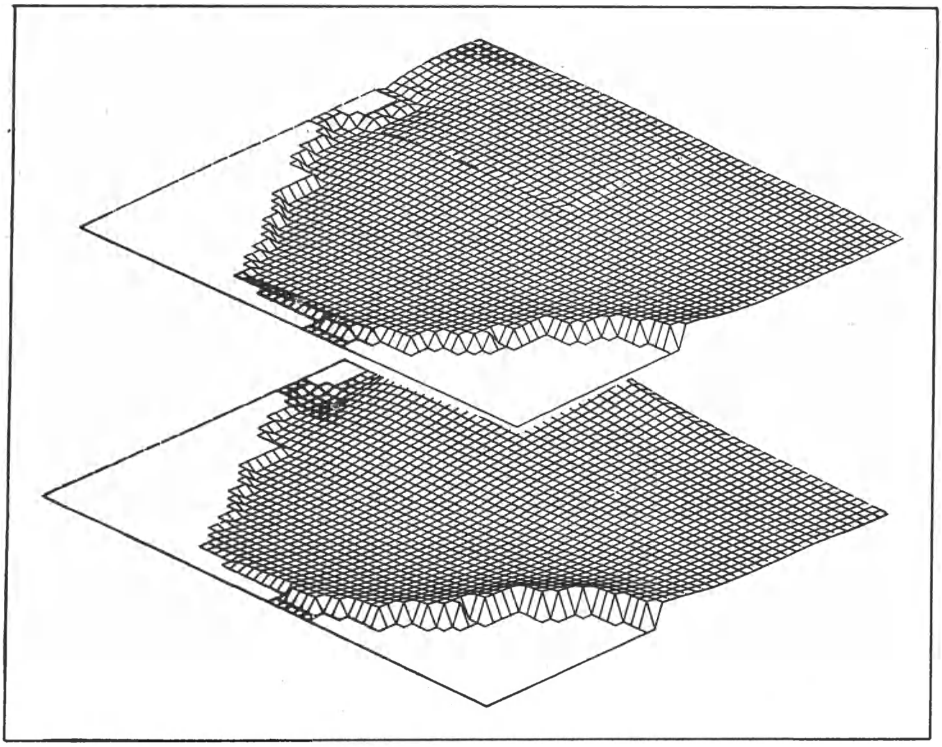

Fig. 11. Simulation of the tides (9 constituents) for the fine grid. (a) tides alone. (b) with wind.

7. CONCLUSION

The emphasis of the research hither to has been put on the development of an ocean model. In spite of the simplification (see ch. 3) this model reproduces qualitatively well the surface phenomena of the ocean. All calculations are carried out on a personal computer and take about 15 min for a tidal cycle. The model can thus be used for operational, i.e. real time purposes.

In the future the model will be extended in order to calculate water temperature. For the simulation of the changes in the marginal ice zone, moving boundaries will be introduced.

ACKNOWLEDGEMENTS

This text presents research results of the Belgian program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsibility is assumed by its authors. The authors wish to thank C.S. Yu and E. Smets for their valuable help in collecting usefull information and interesting discussions.

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SEA-ICE SIMULATIONS IN THE WEDDELL SEA

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

Keywords
Antarctic, Weddell Sea, sea-ice model, leads.

Abstract
A model of sea-ice formation and movement has been developed and applied to a sector of the Southern Ocean including the Weddell Sea and the Drake Passage.

This sea-ice model with leads is described in two parts :

- the thermodynamical component, which represents the freezing and melting processes due to energy fluxes between the atmosphere, ice, and ocean;
- the dynamical component, presently limited to the computation of ice movement due to wind.

Results from this model, including ice thickness, temperature, and spatial extent, will be presented and discussed for a particular point and for the whole area.

1. INTRODUCTION

At the mesoscale, the sea-ice layer can be considered as a two-dimensional continuum **sandwiched** between the atmosphere and the oceans. Thermodynamic and dynamic processes at the air-sea interface constrain the ice and determine its thickness and movement. Ice growth is due to freezing of seawater, and decay is associated with melting. Moreover, external and internal forces cause movement and deformation of the ice layer. These different processes must be taken into account when developing a sea-ice model.

This paper presents the first results of a model of Antarctic sea-ice in a domain centered on the Weddell Sea and the Drake Passage. The goal is to be able to reproduce the observed seasonal cycle of sea-ice extent and thickness. The problem is approached here in two steps, by modelling first the thermodynamical processes (source term) and second the dynamical processes, restricted to kinematic aspects of the sea-ice motion. The model is forced with climatological atmospheric data and a constant ocean heat flux. The ocean currents are not yet taken into account. The results obtained are coherent with the observations and with results from other models. They are presented for one particular point and for the whole area.

2. GEOGRAPHICAL AREA STUDIED

The domain covered by the model extends from latitude 50° S to 80° S and from longitude 80° W to 30° E. It includes the southern tip of South America, the Drake Passage, the Antarctic Peninsula and the Weddell Sea. This area was chosen because other modelling studies made in the same region allow for comparison with their results (Hibler, 1984; van Ypersele, 1986). Moreover, this sector of the Southern ocean is relatively rich in meteorological and glaciological observations.

Both the surface heat fluxes and the wind stress are computed from the climatological data compiled by Taljaard *et al.* (1969). These authors give the monthly mean climatological values of surface air temperature, dew point, surface geostrophic wind and pressure.

The cloudiness, function of both latitude and time, is derived by Parkinson and Washington, (1979) from curves of van Loon (1972). Like a shield, this parameter modulates the radiative fluxes.

Snow is allowed to fall on the ice at a prescribed rate: it is assumed distributed uniformly in time and space with a value of 0.2 m year^{-1} (van Ypersele, 1986).

Figures 1 and 2 present, respectively, the surface temperature and surface geostrophic wind fields on Julian day 90 (March 31) and 270 (september 27). The main meteorological features are :

i) the surface temperature gradients are mostly meridional excepted in the Antarctic Peninsula (fig. 1);

ii) the cold anticyclone over the continent produces the easterly winds along the coast of Antarctic, a clockwise circulation exists in Weddell Sea and the westerly winds are blowing hard (9 to 10 m s^{-1}) around latitude 60° S (fig. 2);

iii) the fractional cloud cover achieves a maximum of 0.85 in January and 0.78 in July at latitude 60° S.

3. THERMODYNAMIC SIMULATION

3.1. Sea-ice model

The sea ice, assumed to be a uniform horizontal slab of ice, is caught in an **energetic** vice due to heat exchanges through the ice-air and the ice-ocean interfaces. At the interface of ice with the atmosphere, a balance of fluxes is assumed to exist between the shortwave radiation available at the surface (solar energy), the latent (humidity) and sensible (temperature) heat fluxes, the longwave radiation from the atmosphere and the ice-surface, and the conductive flux from below the surface. If this balance requires the surface temperature to go below the melting point (-0.1° C for ice), the ice melts and stays at the melting temperature. At the bottom of the ice, the conductive flux within the ice must be balanced by the vertical heat flux from the deep ocean. If it is not the case, the imbalance causes ice to accrete onto the bottom or to ablate from it.

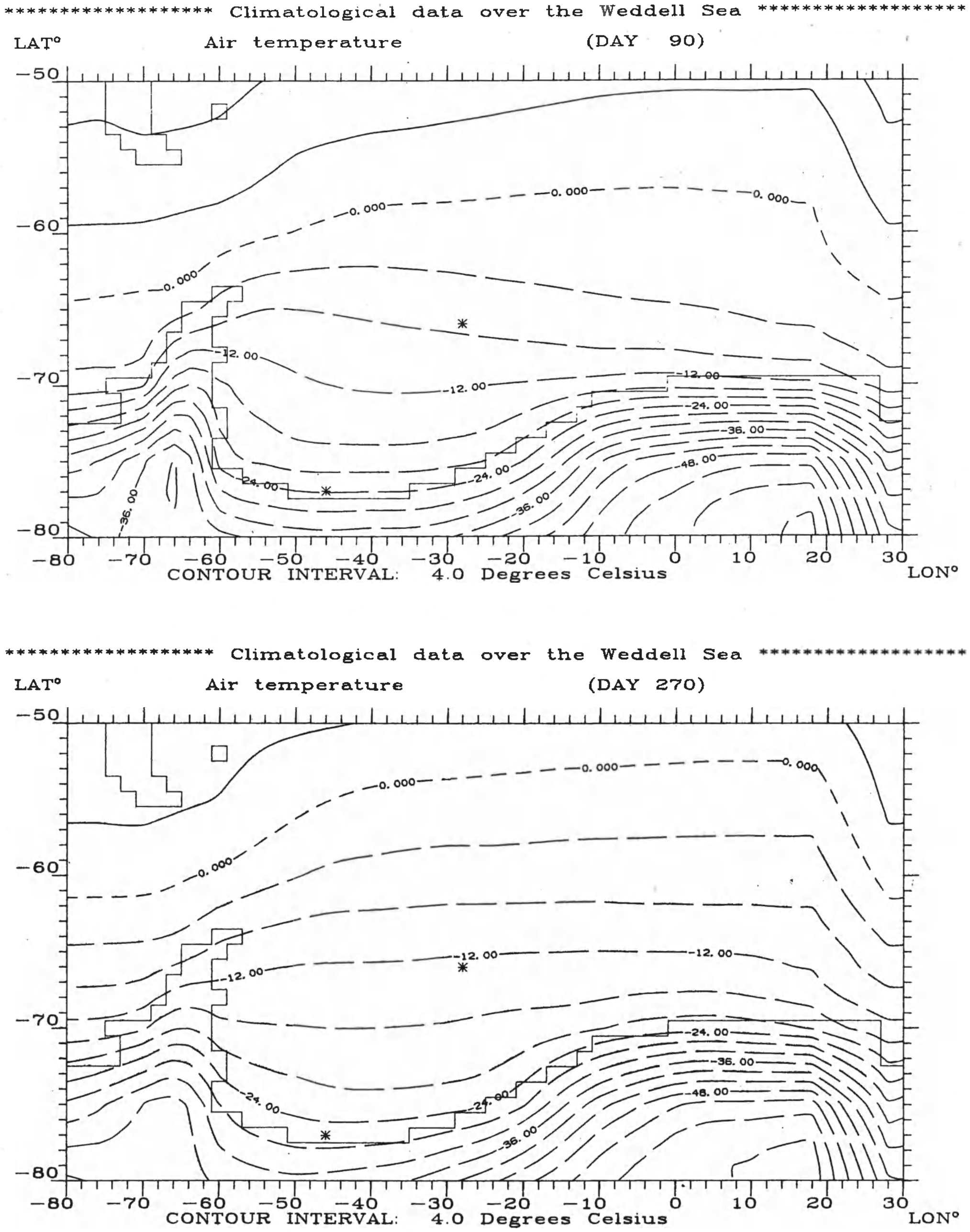

Figure 1 Surface air temperature (°C) on Julian day 90 (top) and 270 (bottom). The southern tip of South America, the Falkland Islands and the Antarctica coasts are represented by a stepwise contour in the model domain. The stars give the positions of particular points with coordinates (47° W, 77° S) and (28° W, 66° S) for which results are discussed. (From the data in Taljaard *et al., 1969).*

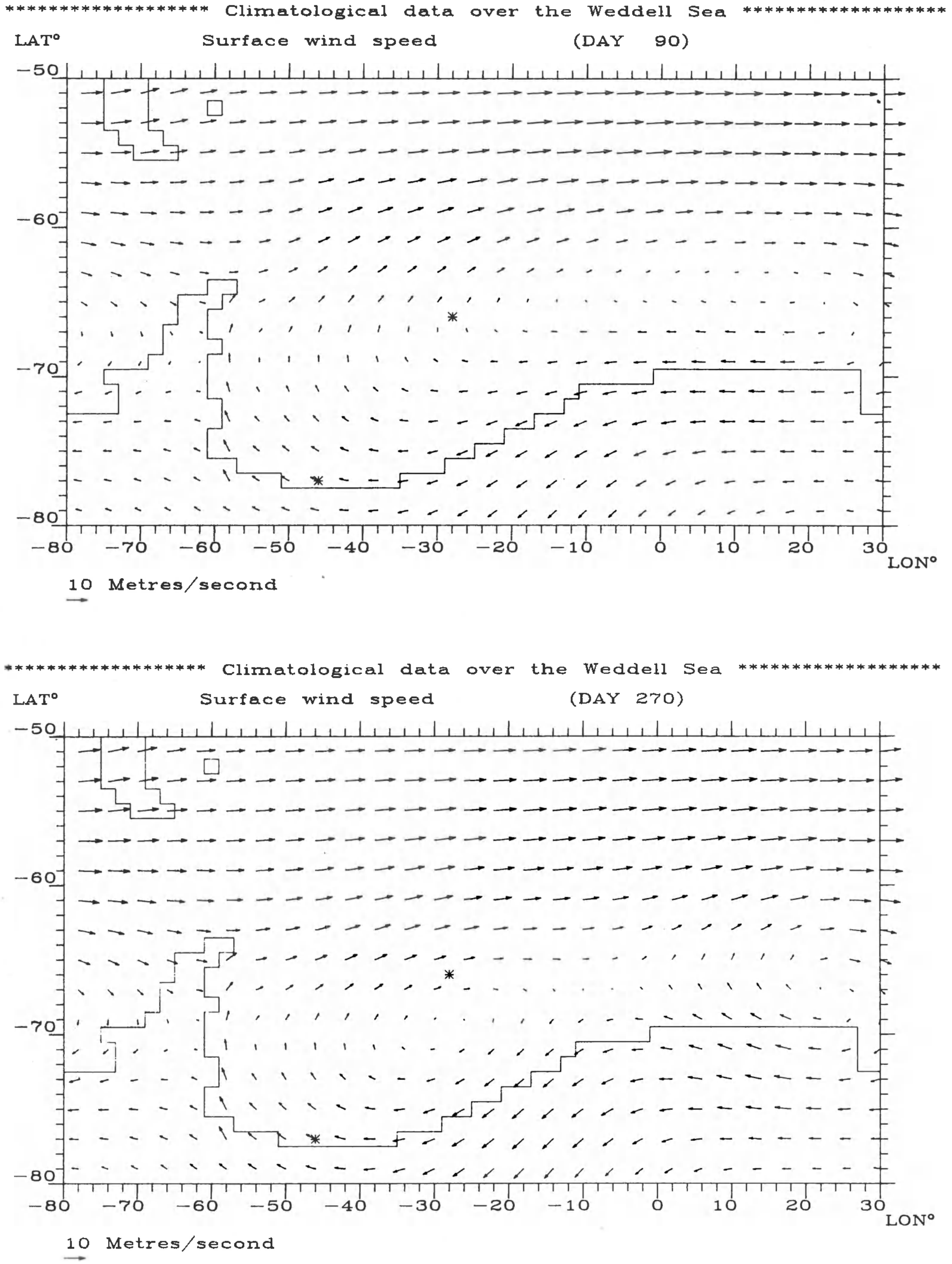

Figure 2 Surface geostrophic wind (m s^{-1}) on Julian day 90 (top) and 270 (bottom). The southern tip of South America, the Falkland Islands and the Antarctica coasts are represented by a stepwise contour in the model domain. The stars give the positions of particular points with coordinates (47° W, 77° S) and (28° W, 66° S) for which results are discussed. (From the data in Taljaard *et al.*, 1969).

The energetic vice allows to calculate, by integration in time, the temperature on the boundaries of the ice. Within the ice, the ice temperature is governed by an one-dimensional heat diffusion equation: the physical phenomena are dominated in the vertical by the balance between the thermal conductivity and the storage of heat in the ice medium per unit time. The penetration of the 17% of the solar energy into the snow-free ice, and its storage in brine pockets is also taken into account. The numerical solution of this set of equations is based on the three-layer model of Semtner (1976) where the slab of ice is represented by two layers of equal thickness, and snow by a third layer. The number of layers is reduced if the ice thickness drops below a critical value.

Since there is little surface melt, snow can accumulate on the ice up to the point where its weight depresses the ice below the water level. Some packed snow is then transformed into "white ice" (Ledley, 1985). This transformation of snow into ice is taken into account after each thermodynamic timestep, and the vertical temperature profile is adjusted accordingly.

3.2. Upper ocean model

The oceanic mixed-layer temperature is computed using energy budget equations applied to a fixed-depth layer 60 m deep. The atmospheric forcing derives from the climatological fields as for sea ice. The deeper ocean is supposed to bring into the mixed-layer a vertical heat flux of 6 W m^{-2}, mean value proposed by Hibler (1984) in the Weddell Sea. The mixed-layer temperature is never allowed to be inferior to the seawater freezing temperature (-1.9° C), and ice starts to grow as soon as this critical point is reached.

3.3. Leads parameterization

In reality, the sea-ice field is more a discrete physical system than a continuous medium. The sea-ice is fragmented in ice floes with different thicknesses (from centimetres for young ice to a few metres for thick or multiyear ice). Those floes are separated by channels of open water (cracks, leads). There can also exist large areas of open water surrounded by ice, called "polynyas". The size of these **open windows** is an important parameter in the total energy budget, because of the difference between the albedo of ice (of the order of 0.8 if snow-covered) and water (0.10), and because of the large difference in latent heat flux over ice or water.

The fractional ice cover is computed first by considering only the thermodynamic aspects, following Semtner (1976) and Maykut and Perovich (1987) as follows:

i) the fractional ice cover, A, cannot exceed a maximum value of 0.98 in the Antarctic due to the continuous presence of leads in the ice (Parkinson and Washington, 1979);

ii) the change in fractional ice cover depends on the surface heat balance of the lead. If this balance is favorable to a warming of the mixed layer, the energy available is used to melt ice laterally, keeping the mixed-layer temperature at the freezing point as long as the ice has not completely melted. If the conditions are favorable to the formation of new ice, this ice is added onto the side of the ice already present until the ice concentration reaches its maximum value. Beyond, the ice thickness increases vertically in order to conserve energy;

iii) to remain in concordance with the upper ocean model, the energy due to the solar radiation penetrating the lead is advected beneath the ice where it increases the oceanic heat flux.

3.4. Application

The three preceding sections define the thermodynamic part of the sea-ice model; the Semtner model, white ice-mechanism and leads parameterization constitute its basic elements. This purely thermodynamic model is now applied to the domain selected.

3.4.1. Set-up

The model is used to simulate the sea-ice annual cycle over and around the Weddell Sea. The model domain is gridded, in a spherical coordinate system, by elements of 2° in longitude by 1° in latitude (56 points in longitude and 31 in latitude). The continents and Falkland Islands boundaries are schematized by stepwise boundaries and the variables are computed in the centre of each mesh. Four meshes of the lattice would roughly cover Belgium.

The restriction of the domain to a section of the Southern Ocean and the zonal character of the ocean and ice circulation suggests a smooth connection of data and simulated fields between the east and west boundaries. Following van Ypersele (1986), this cyclic continuity was established laterally by linearly interpolating the forcing data over five gridpoints west of the eastern boundary. This restricts the interpretation of results to the sector located between longitudes 80° W and 20° E.

The fluxes at the surface of the ice or ocean were parameterized following laws used by van Ypersele (1986) and Fichefet and Gaspar (1987). With these authors, we choose the solar flux parameterization of Shine (1984), the atmospheric longwave radiation is calculated following the Marshunova (1966) formula and the latent and sensible heat fluxes are calculated from standard bulk aerodynamic formula using the same expressions as Parkinson and Washington (1979).

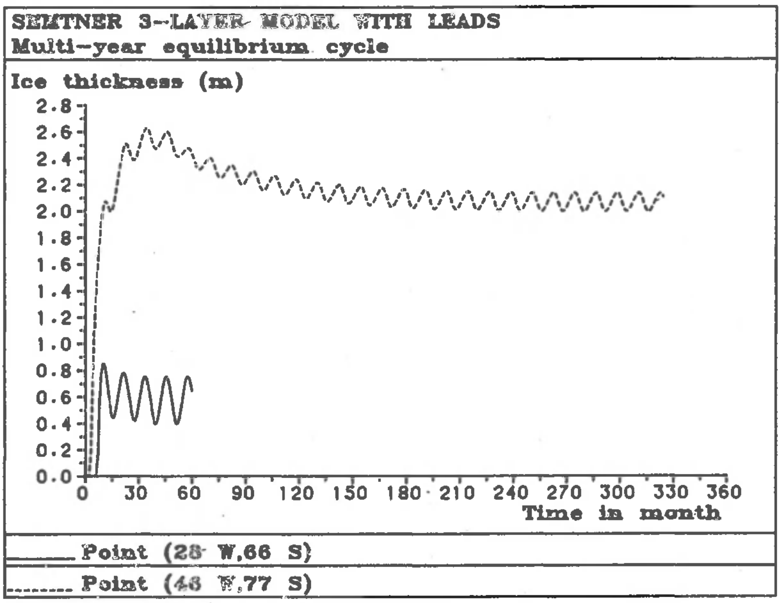

Figure 3 Multi-year equilibrium cycles of the ice thickness at the points (47° W, 77° S) and (28° W, 66° S) for a vertical oceanic heat flux of 6 W m^{-2}.

The absorption of the solar irradiance into seawater is parameterized following Paulson and Simpson (1977) with coefficients defined in Jerlov (1976).

3.4.2. Results

With the forcing defined above, the model is run for ten years with a timestep of one day, starting from ice-free initial conditions on January first. This ten years period is long enough to produce an almost stable equilibrium seasonal cycle of ice thickness. Figure 3 shows the multi-year equilibrium cycle resulting from a thirty-year model run for two particular points: the first near the coast with coordinates 48° W, 77° S and the second in the middle of the Weddell Sea with coordinates 28° W, 66° S. One can see that the annual cycle is stabilized after 5 years for the northern point, and after 26 years for the southern point. Figure 4 shows for the northern point the sensitivity of the ice thickness and its convergence rate to changes in the vertical ocean heat flux. Increasing the ocean heat flux decreases the average ice thickness, and increases the cycle amplitude and its convergence rate. Figure 5 shows for the same point the annual cycle of ice thickness for ocean fluxes of 2, 6, and 18 W m^{-2}. With the latter value, there is no more ice during the summer months.

Figures 6 and 7 show the simulated pattern of ice thickness for Julian days 90 (March 31) and 270 (September 27) with the position of the northern and southern points indicated by a star. The thickness contours on day 90 follow softly the coast of Antarctica with a continuous increase up to a maximum of 2.5 m at the point with coordinates 60° W, 75° S.

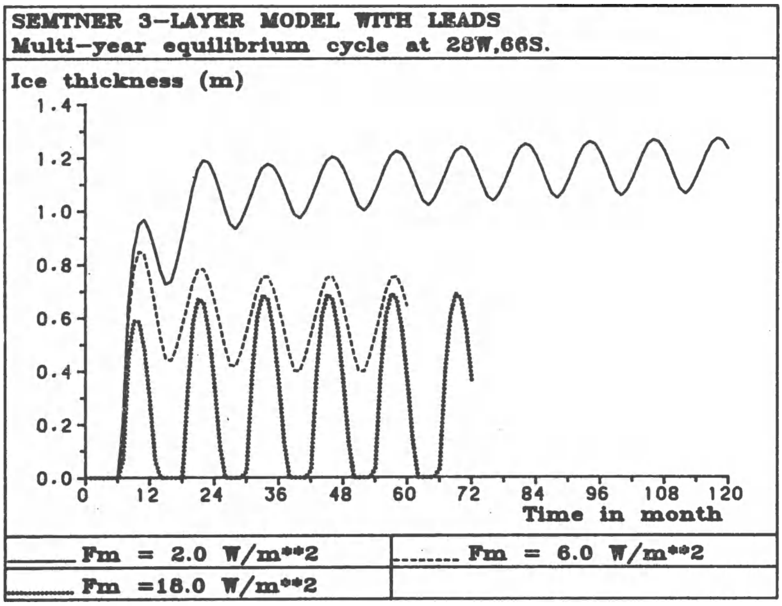

Figure 4 Multi-year equilibrium cycles of the ice thickness for three values of the vertical oceanic heat flux F_m : 2, 6, and 18 W m^{-2}. The model integration is limited to ten years.

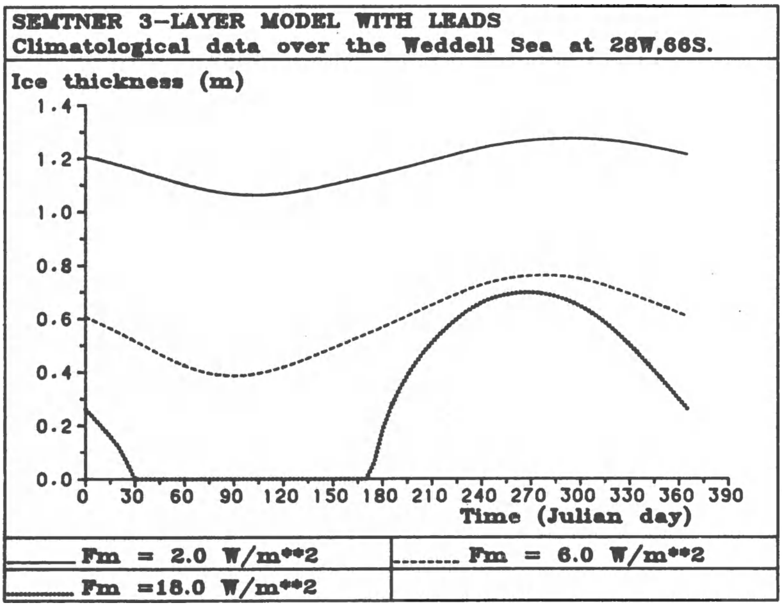

Figure 5 Comparison of annual thickness cycles for three values of the vertical oceanic heat flux F_m : 2, 6, and 18 W m^{-2}

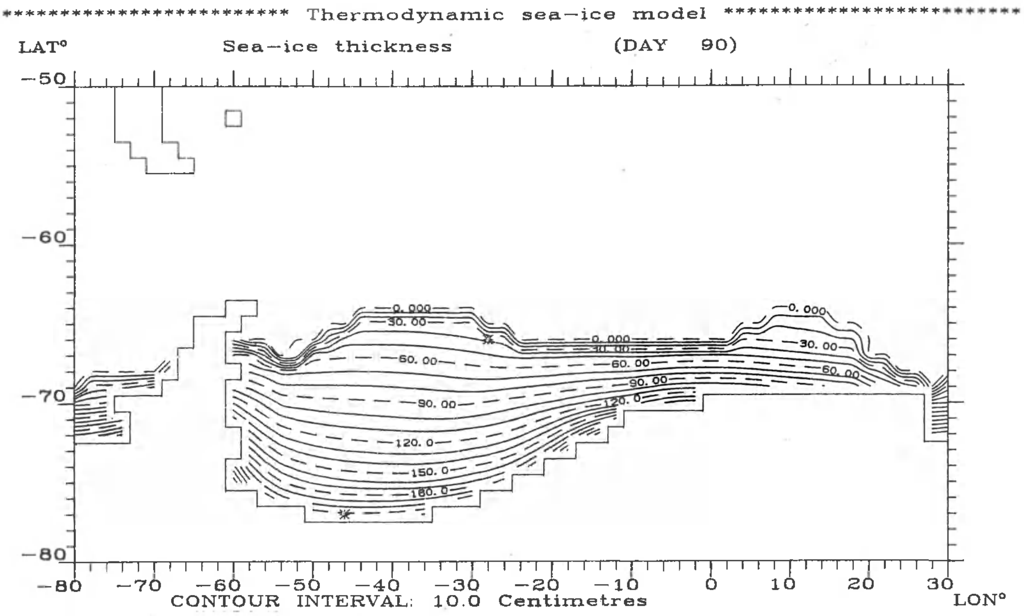

Figure 6 Ice thickness (cm) computed by the thermodynamic sea-ice model for day 90 (March 31) of the tenth year of simulation.

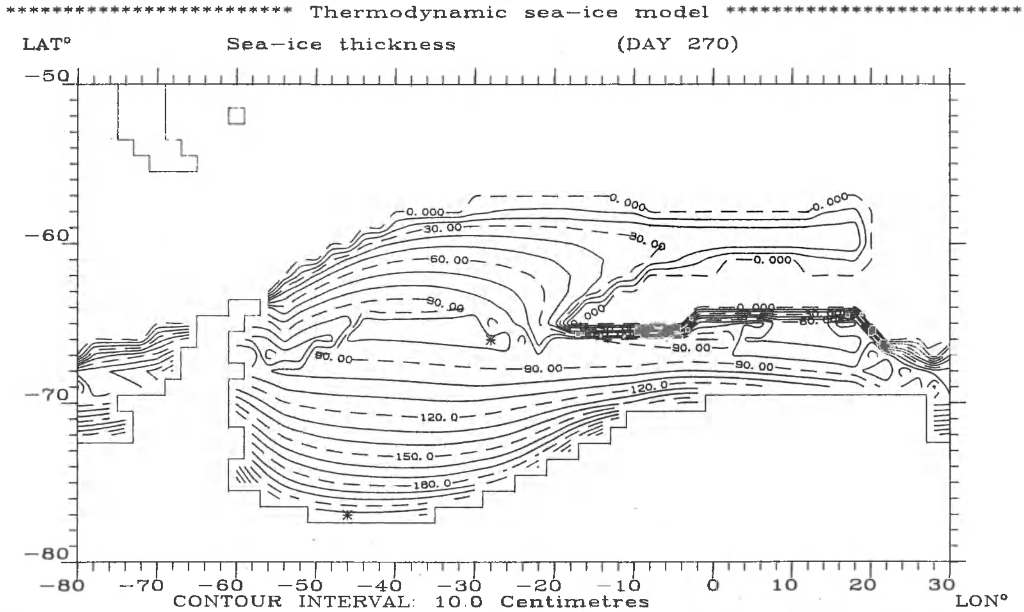

Figure 7 Ice thickness (cm) computed by the thermodynamic sea-ice model for day 270 (September 27) of the tenth year of simulation.

In winter, the ice thickness increases more slowly up to 2.6 m excepted in the middle of the Weddell Sea where there is a slight decrease. Around latitude of 63° S and east of longitude of 16° W, the ocean is free of ice. This open water area, which would appear as a polynya if there was no cyclic continuity, is located in the region where the so-called "Weddell Polynya" has been occasionally observed by satellite (Zwally *et al.*, 1983). A similar polynya had been obtained in simulations involving a coupled sea-ice and ocean general circulation model where the ocean heat flux into the ice was computed instead of being prescribed (van Ypersele, 1986). In the future, we intend to test the sensitivity of the polynya position to a non-constant spatial distribution of the oceanic heat flux.

4. DYNAMIC MODEL

4.1. Ice transport

The ice sea is like a **raft** driven by wind and ocean currents. Its movement derives from the balance of forces acting on it. These forces are the wind and water drag at the air-ice or ice-water interface, the Coriolis acceleration, the gravitational force due to the sea surface tilt, and the internal ice resistance.

A scale analysis shows that, on time scales of a few hours, the inertial term is three orders of magnitude smaller than the wind and water forces (Campbell and Rothrock cited by Parkinson and Washington, 1979). The ice-velocity field is steady and defined from five major forces. Thorndike and Colony (1982) and Lepparanta and Hibler (1987) suggest to neglect the internal ice stress in a first approximation, to assume a geostrophic balance of the Coriolis acceleration by the gravitational force, and to express the ice velocity $\underline{v}_i$ as a linear function of the geostrophic wind $\underline{V}_a$ and the oceanic current $\underline{V}_w$, the first being subjected to a rotation characterized by a deviation angle β:

$$\underline{v}_i = \alpha \exp(-i\,\beta)\, \underline{V}_a + \underline{V}_w \tag{1}$$

From measurements made in the Arctic, Thorndike and Colony found that at more than 400 km from the coasts, this linear parameterization of the ice velocity fits well the observations with the parameters $\alpha = 0.008$ and $\beta = 8°$. Closer to the coasts, the ice stress term should be considered to obtain the ice motion. In the absence of similar measurements in the Antarctic, the same values will be used at each gridpoint, except that the sign of the rotation angle has been reversed, since the domain is the Southern Hemisphere.

4.2. Conservation laws

Wind and ocean currents redistribute the ice mass created at the ocean surface by the thermodynamic processes. This ice mass per unit area M (= ρhA), defined as the product of ice density ρ (constant) by ice thickness h and fractional ice cover A, must be conserved in time following the equation:

$$\frac{dM}{dt} = \frac{\partial M}{\partial t} + \nabla \cdot (\underline{v}_i \, M) = P \tag{2}$$

in which P represents the time rate of change of ice mass due to thermodynamic processes.

A second conservation equation is necessary to take into account the ice convergence and divergence, this ice being considered horizontally incompressible. We require the conservation of the fractional ice cover (concentration or compactness) A with the help of the equation :

$$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \nabla \cdot (\underline{v}_i \, A) = Q \tag{3}$$

where Q represents the time rate of change in ice concentration due to thermodynamic processes. The set of two equations (2) et (3) yields a conservation equation for the ice thickness h. A similar conservation equation is obtained for snow thickness.

For numerical stability, a numerical diffusivity term is added to the right-hand member of each conservation equation. An empirical value of 8000 $m^2 \, s^{-1}$ is used for the horizontal mixing coefficient. In order to maintain a uniform grid Reynolds number (product of the velocity by the grid spacing divided by the diffusivity) in a non-uniform grid in cartesian coordinates, the mixing coefficient varies with the latitude following a relation proposed by Blumberg *et al.* (1984).

Since the interpolation introduced some non-zero divergence in the climatological wind field, and since the ice velocity field is linearly related to the wind, a term containing the product of the divergence of the ice velocity field by the variable to conserve is added on the right-hand side of each conservation equation (Kitada *et al.*, 1984).

Finally, after each thermodynamic timestep, the conservation equations for ice thickness, ice compactness, and snow are numerically solved with Wang (1985) flux corrected transport scheme, which combines an upwind scheme with a centered one to avoid the numerical ripples.

When the ice moves into a grid cell where the temperature is higher than the freezing point, the available energy in the oceanic mixed layer is used to melt the ice layer, and the mixed-layer temperature is adjusted.

4.3. Application

4.3.1. Set-up

The transport parameterization described above is added to the thermodynamic model in the same numerical and physical configuration. Sea-ice thickness and effective ice area (the total ocean surface covered by sea ice, excluding all open water within the ice pack) are computed starting from an ice-free state. To allow for comparison with observations, the effective ice area is calculated between longitudes 60° W and 20° E to correspond with the Weddell Sea sector for which satellite observations have been analyzed by Zwally *et al.*, (1973).

4.3.2. Results

Figures 8 and 9 show the pattern of ice thickness for days 90 (March 31) and 270 (September 27) of the tenth year of integration. Along the eastern side of the peninsula and at the point with coordinates 60° W, 74° E, the ice reaches a maximum thickness of 2.6 m at day 90 and 3.6 m at day 270. The main differences between these results and those obtained without including any ice transport are:

i) weaker ice thickness gradients;

ii) a rotation of the contours under the influence of the ice velocity field;

iii) the persistence of open water at the latitude 63° S on a width of two grid cells;

iv) a larger amplitude of the ice thickness seasonal cycle under the effect on ice convergence-divergence.

The ice thickness difference between the northern and southern sides of the open water area could be explained by the non-transport of the ice- and snow-temperature fields.

Figure 10 shows the simulated annual cycle of effective ice area produced with and without ice transport added to the thermodynamic processes. Both cycles admit a common maximum of the order of 5×10^6 km^2 close to day 270 (September 27). Minima are very different: the effective ice area reaches a minimum value of 2.6×10^6 km^2 on day 80 (March 21) without ice transport, and 1.2×10^6 km^2 on day 35 (February 4) with transport. The simulated growth periods are thus respectively 200 or 235 days long, and the decay periods are 165 or 130 days long. These values can be compared to the values given by Zwally *et al.* (1983) in the Weddell Sea sector. They found an average minimal effective ice area with concentrations higher than 0.85 of 0.8×10^6 km^2 in mid-February and a maximum of 5.2×10^6 km^2 in mid-September (Figure 11). The observed growth period is thus 210 days long, and the decay is 155 days long. This comparison shows that the thermodynamic-only model reproduces the growth and decay periods of the annual cycle of the sea ice. The inclusion of parameterized ice dynamics improves significantly the reproduction of the amplitude

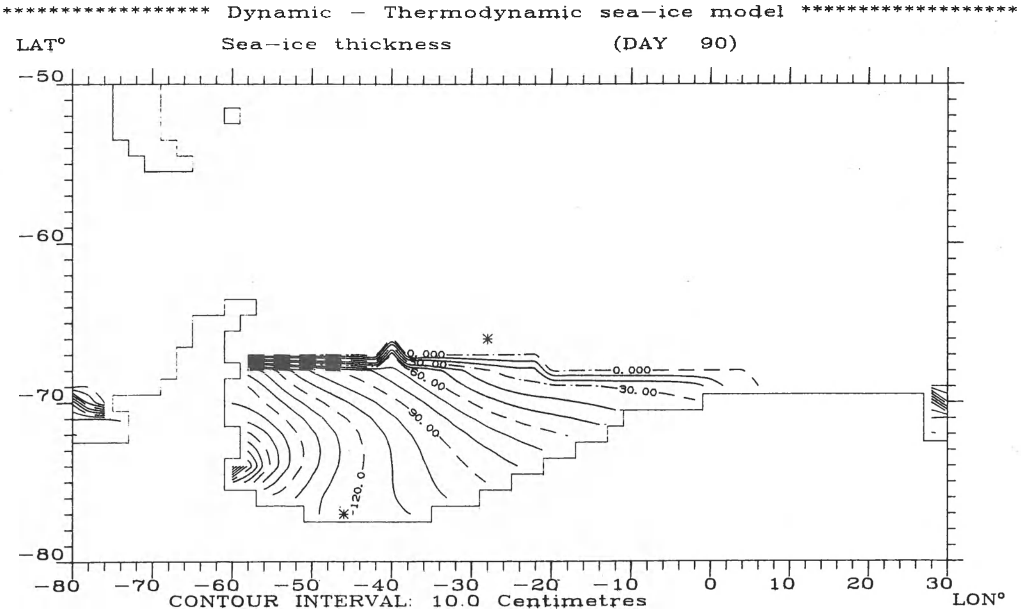

Figure 8 Ice thickness (cm) computed by the thermodynamic-dynamic sea-ice model for day 90 (March 31) of the tenth year of simulation.

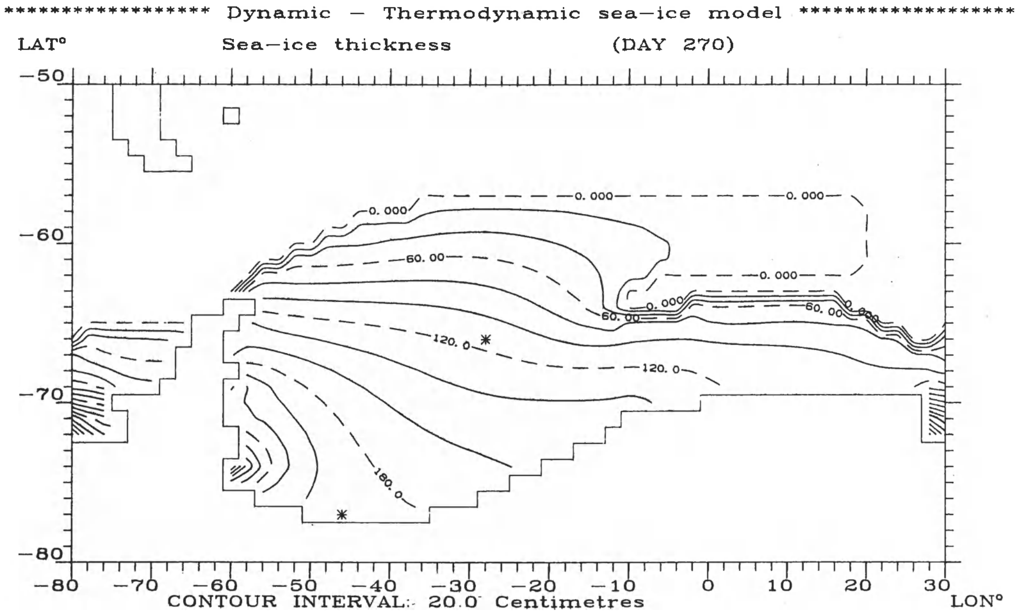

Figure 9 Ice thickness (cm) computed by the thermodynamic-dynamic sea-ice model for day 270 (September 27) of the tenth year of simulation.

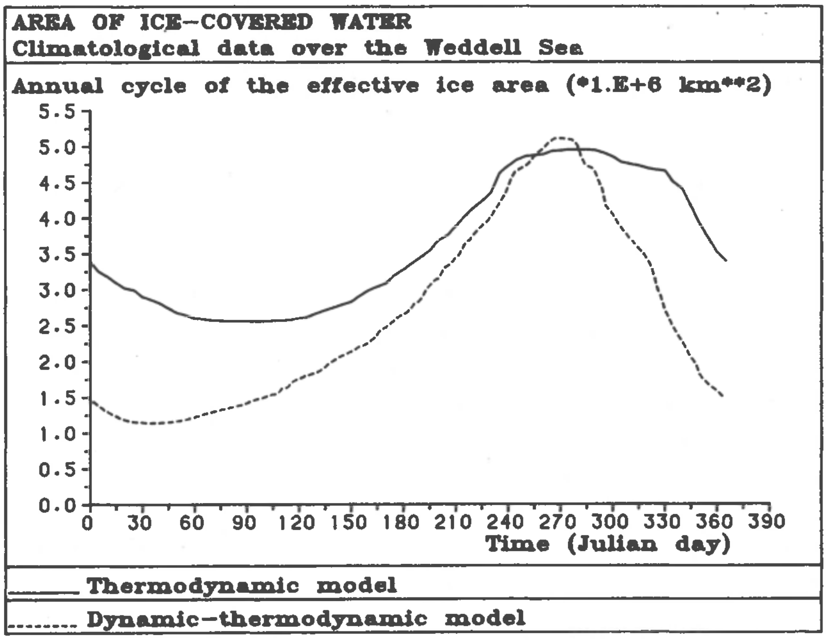

Figure 10 Annual cycle of the effective ice area computed by the sea-ice model without (solid line) and with (dashed line) transport.

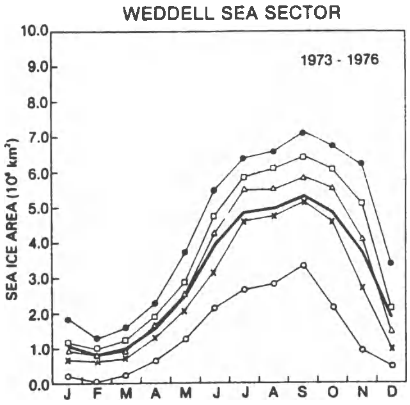

Figure 11 Yearly cycle of ice extent (total area of grid squares containing any amount of ice) and effective ice area (the total ocean surface covered by sea ice, excluding all open water) as observed in the Weddell sector between 1973 and 1976 (x 10^6 km^2). The thick curve is for the effective ice area and the top curve for the ocean area covered by sea ice concentration higher than 0.85 (from Zwally *et al.* 1983).

and phase of the seasonal cycle. This had previously been shown for the Antarctic by Hibler (1984) and van Ypersele (1986).

5. CONCLUSIONS

The goal of this study was the development of a sea-ice model based on the major thermodynamic and dynamic processes. This model was applied to an important sector of the Southern Ocean including the Weddell Sea and Drake Passage. The atmospheric forcing was derived from climatological data, and the ocean forcing was reduced to a constant heat flux into the ice, considering an ocean at rest.

Two simulations were presented. The first included only the thermodynamic processes of sea-ice building and was performed with an oceanic heat flux set to a constant 6 W m^{-2} and a minimum open-water fraction of 2% of each grid cell. The results (see Table I) showed a seasonal cycle of effective ice area with an insufficient amplitude. A much better agreement, both for amplitude and phase, was obtained in the second simulation which included ice transport effected by wind.

To improve the model, it is projected to include the advection of thermodynamic fields, the effect of ocean currents, and the effect of a non-uniform oceanic heat flux into the ice.

Table I. : Comparison of sea-ice simulations with observations (Zwally *et al.*, 1983)

	Date_{min}	Area_{min} $\times 10^6$ km^2	Growing days	Date_{max}	Area_{max} $\times 10^6$ km^2	Decay days
Observ. (1973-76)	Feb. 15	0.8	210	Sep. 15	5.2	155
Thermo. only with leads	Mar. 21	2.6	200	Oct. 7	5.0	165
Thermo.+dyn with leads	Feb. 4	1.2	235	Sep. 27	5.1	130

6. ACKNOWLEDGEMENTS

The authors wish to express their thanks to Prof. A.J. Semtner (Naval Postgraduate School, CA., U.S.A) for the use of his thermodynamic model. They also appreciated suggestions from Mr. T. Fichefet (Université Catholique de Louvain, Louvain-la-Neuve, Belgium) on sea-ice modelling. Thanks are due to Mr. J. Castel Branco and Mrs. Ch. Coolen for making the figures and Ms. A.F. Lucicki for typing the manuscript. The following text presents results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsability is assumed by its authors.

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DYNAMICS OF THE ANTARCTIC ICE CAP
Part I : Ice thickness measurements related to the damming effect of the Sør Rondane, Dronning Maud Land, Antarctica

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

ICE THICKNESS MEASUREMENTS IN THE SØR RONDANE

Key Words : Ice Thickness measurements, Gravity, Ice Sheet, Damming Effect, Sør Rondane

Abstract : *Preliminary results of the 1986-87 Belgian Participation in the JARE 28 Expedition to the Sør Rondane , Antarctica, are presented. The principles of ice thickness calculations, based on gravity measurements, are given. The subglacial results illustrate the damming effect of a coastal mountain range and indicate an ice covered landscape in the process of being cut-off from the main plateau ice supply.*

1. Introduction

The East Antarctic Ice Sheet screens off most of the direct glacio-geologic information on the bedrock and restricts the observations to a few isolated mountain areas and the oceanographic sediments. Most of the information regarding the glacial history has come from investigations in the Trans Antarctic Mountains (Mayewski and Goldthwait, 1985). However a large body of information can also be found on the nunataks and in some dry valleys situated in the mountain ranges bordering the coast of Dronning Maud Land, Enderbyland and a few other marginal areas of the East Antarctic ice shield. In contrast with the Trans Antarctic Mountains some of these areas are quite close to the present ice divide. The recorded variations within the sediments of these mountains might therefore correspond quite closely to fluctuation in altitude and/or shifts of the position of the East Antarctic ice divide.

Apart from providing the necessary data on the dynamics of the ice cap the marginal coastal mountains constrain the ice movement and create typical outlet glaciers. As such they can be said to contribute to the stability of the Antarctic ice sheet. The Sør Rondane Mountains provide a particular beautiful example of the damming effect of such a coastal mountain range.

This paper presents some preliminary results from ice thickness measurements obtained in the central part of the Sør Rondane Mountains during the austral summer 1986-87 while participating in the 28th Japanese Antarctic Research Expedition. A complete survey of all the ice thickness profiles and an evaluation of the gravimeter ice thickness determinations as compared to radio echo sounding will be given elsewhere (De Vos and Decleir, 1988 ; Decleir et al., 1988). These ice thickness profiles will serve later as basis for reconstructing the subglacial relief in this part of the Sør Rondane and for interpretation of the glacier dynamics.

2. Ice Thickness Measurements

Over the vast ice covered areas of continental ice sheets -remote from steep mountain ranges and nunataks- the infinite slab method to calculate ice thickness from gravity measurements has been widely used in the past. The method was particularly useful for rapid ice thickness determinations between seismic reflection stations of oversnow traverses during and following the IGY.

The method became largely obsolete when airborne radio echo sounding was introduced in the late sixties. The latter method allowed for the first time rapid and accurate measurements to be made over terrain which is characterized by difficult and dangerous access. Since that time large scale mapping of the subglacial relief became possible and was carried out both over Eastern and Western Antarctica (Drewry, 1984).

However, within the mountain ranges, over narrow outlet glaciers, cirque glaciers etc..., both methods suffer largely from disturbing effects of the valley sides : e.g. side reflections and moraine cover for radio echo sounding, difficult topographic and subglacial modelling for the gravimetric method.

Van Autenboer and Blaiklock (1966) and Van Autenboer and Decleir (1974, 1978) applied the gravimetic method systematically in an approach to estimate the total glacier discharge through a 220 km long mountain range (Sør Rondane). Cross sections over the most important drainage glaciers were constructed using Talwani's method for modelling 2-D gravity anomalies.

During the 1986-87 JARE 28 Expedition a detailed investigation was planned of the subglacial morphology within the central part of the Sør Rondane by comparison of ice radar and gravity measurements. In that respect use was to be made of a newly developed "backpack" radio echo sounder (Scott Polar Research Institute). It was assumed that, especially near the valley walls and over the moraine covered ice surface, such a portable instrument would be advantageous.

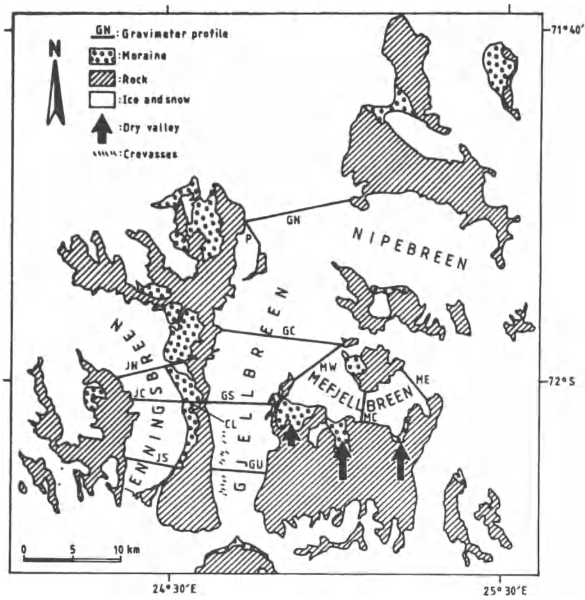

Figure 1 : Central Part of the Sør Rondane and Gravimeter Profiles

However due to stability and power problems with the radar system in the field, the ice thickness determinations were mainly restricted to gravimeter measurements. Gravity measurements were performed with a standard Worden gravimeter. 11 Gravimeter traverses were carried out across the glaciers of the central part of the Sør Rondane (fig. 1). As these profiles were chosen between well identifiable points on rock at both sides of the glacier location and distance between stations could be easily recorded on the mileage reader of the snow scooters. In the middle of the glacier spacings between stations were generally 0.5 or 1 km while altitudes were determined by aneroid altimetry. However near the valley-sides position and altitude of the gravimeter stations, both on the glacier and on the adjacent rock, were determined by theodolite tacheometry. Here the distance between stations varied between 100 and 500 m. As most of the profiles were measured to and fro, altitudes and gravimeter measurements were taken as the mean value, thereby automatically correcting for drift phenomena.

The gravity values were first corrected for latitude and height. To obtain a relatively fast and easy-to-handle calculating model the traditional Bouguer and terrain corrections were replaced by a "zonal" correction algorithm (fig. 2). The outer zones of the model (Topo $_{out}$) contribute a relatively minor amount to the total attraction values of the surrounding rock, therefore each outer zone can be approximated by a semi infinite slab, similar to the tradional Bouguer correction. The inner zones adjacent to the glacier (Topo_{in}) are much more important for the measured attraction forces. For this zone the total mass above the reference level was calculated by the Talwani method. The latter method allows the gravity effect of an arbitrary two-dimensional mass to be calculated by a polygonal approximation of the body (e.g. Telford et al.,). The surface profile of this body was digitized from existing topographic maps.

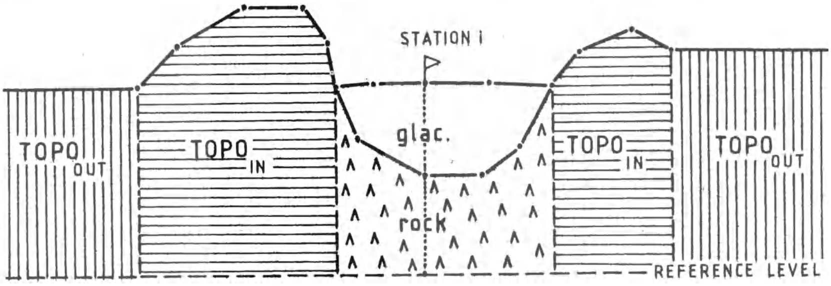

Fig 2. Zonal subdivision of terrain for ice thickness calculations

Finally the attraction of the two masses underneath the glacier surface ($g_{glac.}$ and g_{rock}) are calculated. The first mass is the glacier mass and the second one is the mass of rock which lies between the glacier bedrock and the reference level. The interface between these two masses is the unknown subglacial topography.

The true value G_i at station i can now be decomposed as follows :

$$G_i = \gamma_i - c_{h,i} + g_{topo,i} + g_i \qquad (1)$$

where γ_i is the gravity underneath station i at the reference level.

$c_{h,i}$ is the altitude (free air) correction to pass from the reference level to the altitude of station i

$g_{topo,i}$ is the gravity effect at station i of all the masses between the reference level and the topographic surface except for the area covered with glacier :

$g_{topo,i} = g_{topo,out} + g_{topo, in}$

g_i is the gravity effect of both the glacier ice and the rock beneath the glacier :

$g_i = g_{rock,i} + g_{glac,i}$

On the other hand, the true value G_i at station i is also equal to :

$$G_i = g_{m,i} + g_{ref} + \varepsilon_i \qquad (2)$$

where $g_{m,i}$ is the measured relative gravity value

g_{ref} is the unknown gravity corresponding to the zero of the scale of the gravimeter

ε_i is the error

Since the thickness of the earth's crust and the density of the crustal material may vary, both changes can be approximated by a linear variation of the gravity along the reference level :

$$\gamma_i = \gamma_o + rg\, \Delta x_i \qquad (3)$$

where Δx_i is the linear distance along the profile reckoned from the reference station which is characterized at the reference level by a gravity value γ_o.

rg is the regional gradient in mgal/m

As the hight of the bedrock underneath the glacier is unknown, g_i can only be calculated from a model. If the model is not correct the gravity g_i will differ by an amount v_i,

$$g_i = g_{c,i} + v_i \tag{4}$$

Combining eqs. (1), (2), (3) and (4) and applying them to station i, and to a reference station i = o, one finds after substraction :

$$\Delta g'_i + (\varepsilon_i - \varepsilon_o) = rg\, \Delta x_i + \Delta g_{c,i} + (v_i - v_o) \tag{5}$$

Δ in general stands here for the value at station i minus the value at the reference station

$\Delta g'_i$ combines the measured values plus correction terms :

$$\Delta g'_i = \Delta g_{m,i} + \Delta c_{h,i} - \Delta g_{topo,i}$$

Since the gravity is essentially vertical the numerical solution of eq. (5) can be split up in two parts :

(i) over rock, the ice depths are relatively unimportant and it will be assumed that $(v_i - v_o) \approx 0$. A least squares solution will then give an estimate for the regional gradient rg.

(ii) with the knowledge of the regional gradient and an estimate for the height of the bedrock underneath each station the correction terms v_i can be computed. With these v_i the bedrock altitudes can be inproved and a new regional gradient rg and new v_i can be calculated and so forth. This converges towards constant values of the bedrock altitudes underneath the stations on ice.

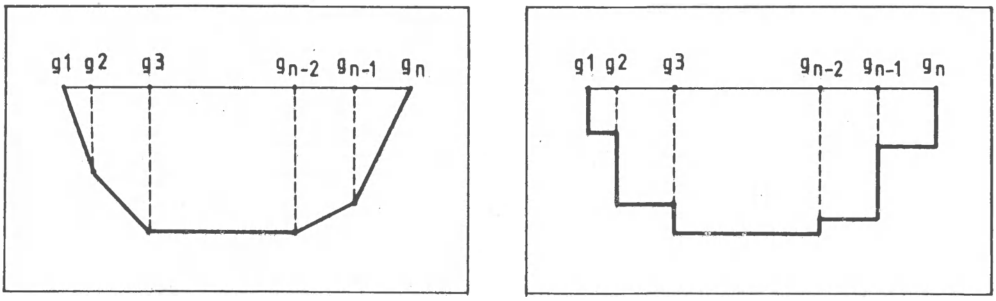

Fig 3. Polygonal (left) and prism (right) approach of subglacial relief.

The approximation of the bedrock by a polygonal line is one way to approximate the outline of the subglacial relief. One can also compose the ice mass and the rock underneath by a set of vertical prisms, extending from the bedrock to the ice surface and from the bedrock to the reference level (e.g. Børsting Pedersen, 1977). Each prism has a gravimeter station as boundary in the x-direction. Fig. 3 compares schematically the two methods. It is clear that both methods converge if the number of stations becomes large. However for a small number of measuring stations the methods diverge significantly. The negative effect of the vertical ice prism near the valley side results generally in a deeper glacier-bedrock profile. Fig. 4 illustrates the polygonal and prism method as applied to one of the profiles.

3. Results

Van Autenboer and Decleir (1974, 1978) have already emphasized the fact that the ice discharge of the glaciers of the central part of the Sør Rondane is very low as compared to the values obtained on the eastern and western side of the range. Although Jenningsbreen (for location see fig. 1) is still connected with the ice of the polar plateau, its mass flux (0.3 10^9kg/km/yr) is comparable to that of the very local glaciers. The same authors found the bedrock of Jenningsbreen to be situated at approximately -150m in the area where this glaciers enters the piedmont region north of the mountain range. Fig . 4 shows an ice thickness profile further up the glacier (Jenningsbreen JN)

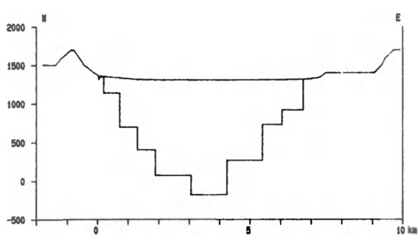

Fig 4. Polygonal (above) and prism (below) model for Jenningsbreen JN

and suggests that this low subglacial relief is continued following the glacier within the mountain range. It is only when approaching the head of the glacier that a steep bedrock rise occurs. This can be seen on fig. 5 where profile Jenningsbreen JS is shown. The latter profile -situated 10 km further upstream from profile JN- at the foot of the ice fall leading to the polar plateau, indicates an ice floor of more than 500m above sea level. Another interesting feature of this southern profile is its asymmetry. The deepest part of the glacier has clearly shifted to the east. This corresponds with a strongly eastward curving of the surface flow-lines as the glacier cuts its gorge through the southern border of the mountain range.

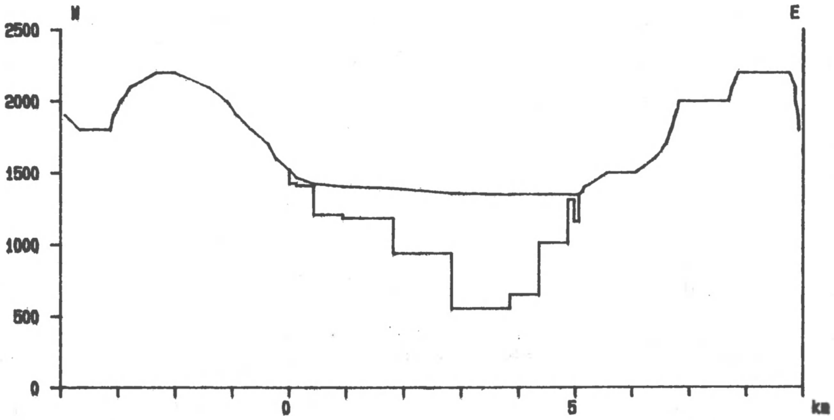

Fig 5. Subglacial Profile for Jenningsbreen JS

Noteworthy is the east-west gradient in the ice surface topography with the higher elevations occurring over the more shallow western part of the glacier. This higher glacier surface is characterized by an eroded snow cover and contrasts with the bare blue ice of the lower east side. Fig (6) shows the ice thickness results for Gjellbreen (profile GC). Although Gjellbreen flows parallel with Jenningsbreen it is fed not only by ice descending from the polar plateau but also from the east by two minor glaciers (Mefjellbreen and Nipebreen) which flow perpendicular to the main

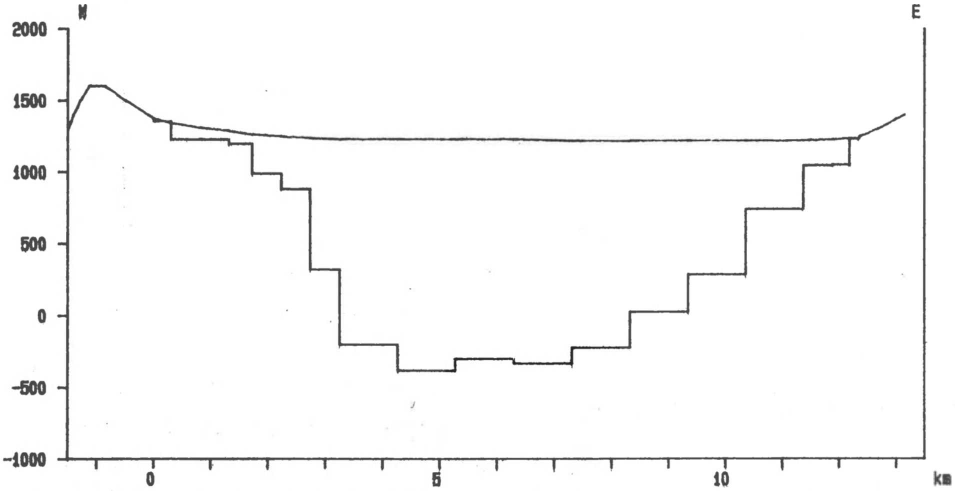

Fig 6. Subglacial Profile for Gjellbreen GC

direction. Mefjell- and Nipebreen divide the central part of the Sør Rondane in multiple blocks. The cross section through Gjellbreen (GC) shows a subglacial depth of -500m which is deeper than the depth measured further to the north (Gjellbreen GN) where -100m is reached. This overdeepening of the glacier is confirmed on profile Gjellbreen GS where the subglacial floor lies also well below sea level. Such overdeepening has been typically attributed to fjordglaciers. Similar findings were reported by Van Autenboer and Decleir (1978) for Hansenbreen.

Three N-S cross-sections of Mefjellbreen show an interesting feature which contradicts somewhat the apparent block faulted appearance of this part of the range. As can be seen on fig. 7 both the eastern profile (ME) and the western profile (MW) are much deeper than the central profile (MC) where the subglacial bedrock remains above 500 m and suggest a subglacial ridge connecting Mefjell and Menipa.

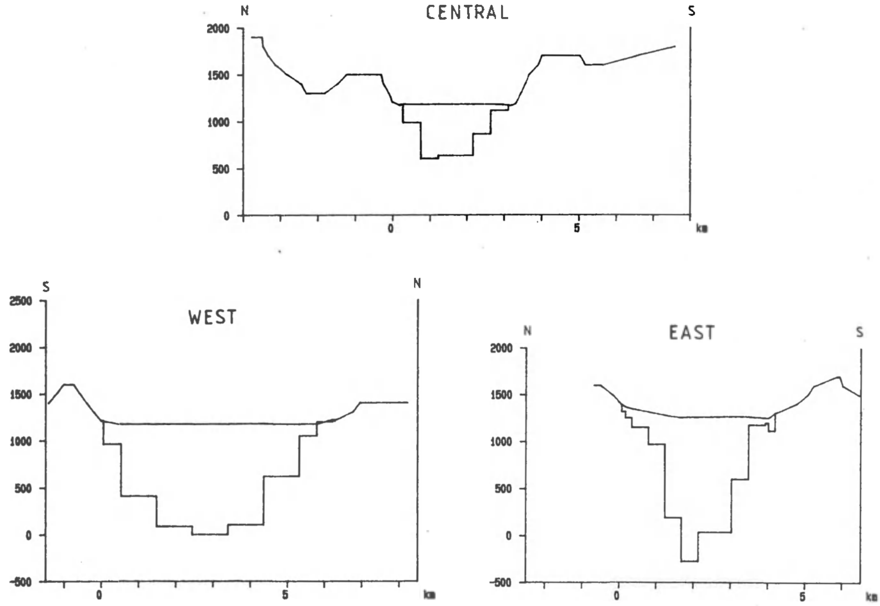

Fig 7. Subglacial Profiles for Mefjellbreen MW (West) Mefjellbreen MC(Central) and Mefjellbreen ME (East).

Further to the south on Gjellbreen the ice thickness decreases rapidly, although the very shallow profile of Gjellbreen GU is still being investigated for possible measuring and modelling errors. Anyway, an ice depth of less than a few hundreds of meters seems very likely. This underscores the damming effect of the southern threshold of the range on the ice flux towards the north. However, Van Autenboer and Decleir (1978) found a significant higher mass flux (6.0 10^9kg/km/yr) for Gjellbreen than for Jenningsbreen. This can only be partly explained by the additional inflow of ice through Nipebreen and Meffellbreen and needs therefore further investigation.

4. Conclusion

There is enough glacial evidence to conclude that two glaciers in the central part of the range, which in the past have developed characteristic glacial valleys similar to the major outlet glaciers, are in the process of being cut-off from the main ice supply. It is interesting to speculate that these on-going processes are similar to those which have led to the existence of the N-S trending dry valleys of neighbouring Mefjell area (fig. 1) and corroborate other glacial geological and geomorphological phenomena observed in the Sør Rondane (e.g. Van Autenboer, 1964). The consequence for possible related changes in position and altitude of the ice divide immediately to the south of the Sør Rondane and of the grounding line of the ice sheet to the north is currently being investigated by numerical modelling.

5. Acknowledgement

The authors are deeply indebted to Prof. T. Hoshiai, leader, and to all expedition members of JARE 28, especially their field compagnons of the Sør Rondane Party K. Hirakawa (leader), N. Matsuoka, Y. Osanai, Y. Takahashi, T. Sakiyama and K. Tanaka. This publication presented results of the Belgian Program "Scientific Research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsibility is assumed by its authors.

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DYNAMICS OF THE ANTARCTIC ICE CAP
Part II : Sensitivity experiments with a numerical ice sheet model with full thermo-mechanical coupling

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

SENSITIVITY EXPERIMENTS WITH A NUMERICAL ICE SHEET MODEL

Key words: ice sheet, numerical modelling, thermo-mechanical coupling, Vostok ice core

Abstract: *An efficient numerical ice sheet model, including time dependence and full thermo-mechanical coupling, has been developed to investigate the thermal regime and overall configuration of a polar ice sheet with respect to changing environmental conditions.*

From basic sensitivity experiments, in which a schematic East-Antarctic Ice Sheet is forced with a typical glacial-interglacial climatic shift, it is found that (i):the mutual interaction of temperature and deformation has a stabilizing effect on its steady state configuration and (ii) in the transient mode, this climatic transition initially leads to increased ice thickness due to enhanced accumulation, whereafter this trend is reversed due to a warmer base. Time scales for this reversal are of the order of 10^3 years in marginal zones and of 10^4 years in interior parts.

Time-dependent modelling of the Vostok flowline, indicates that the Vostok Station area has risen about 95 m since the beginning of the present interglacial due to thermo-mechanical effects, which is of particular interest in interpreting the palaeoclimatic signal of the obtained ice core there.

1.Introduction

In polar ice sheets, ice flow and its thermodynamics are strongly related: temperature determines to a large extent the viscosity of ice so that for a 10 K temperature change, strain rates, for a given stress, change by an order of magnitude, thereby constituting a major factor in controlling the flow characteristics and shape of large polar ice sheets.

Physically, the interaction of temperature and flow comprises a positive feedback mechanism with regard to (sudden) global climatic changes, so that, in principle, creep instability may occur: the increasing ice temperature - increasing strain rate - increasing dissipation feedback-loop, may, under suitable circumstances, lead to a runaway temperature increase, resulting in extensive basal melting, ultimately bringing a continental ice sheet in the surging mode. The potential importance of creep instability in destabilizing the East Antarctic Ice Sheet has been stressed by several authors (Clarke et al. 1977; Schubert and Yuen, 1982; Yuen et al., 1986). However, as became clear in Huybrechts and Oerlemans (1988), the major objection against these analyses is that they are "local" : horizontal temperature advection and driving stress (ice sheet geometry) are not allowed to react to the changing temperature and velocity fields. The development of a creep instability in the aforementioned studies appears to be essentially the consequence of a basic shortcoming in model formulation, namely the neglect of horizontal heat advection, so that a basic damping mechanism is excluded.

From a climatological point of view, on the other hand, interpretation of temperature-depth profiles and isotopic composition of deep ice cores provides evidence of the history of climate, once we understand how ice sheets move and vary under changing conditions. To study the interaction of the physical processes involved, it is necessary to solve the equations governing ice-flow mechanics together with the thermodynamic equation in a fully time-dependent fashion. Historically, the first papers on the temperature distribution in ice sheets did not deal with the interaction of velocity and temperature, but were attempts to give a theoretical explanation for observed temperature profiles (e.g. Robin, 1955; Weertman, 1968; Philberth and Federer, 1971). In these calculations simple one-dimensional (vertical) steady-state models were involved. Due to the neglect of horizontal advection these models could only be applied in regions close to the ice divide. The moving-column model, based on a vertical model, but taking into account in a crude way the effect of horizontal advection, has subsequently been used to investigate two-dimensional (vertical plane) temperature distributions, see for example Budd et al. (1971) where this model is used extensively under steady-state conditions to assess the "Derived characteristics of the Antarctic Ice Sheet". This approach has been used widely by the Australian group since, also in more dynamic situations (e.g. Budd et al. ,1976; Young, 1981; Budd et al. , 1984). Critical to the applicability of the moving-column model is the vertical shear in the horizontal velocity as the assumption that the column remains vertical is not realistic far from an ice divide. Nevertheless, when ice motion is almost entirely by basal sliding, or when all velocity shear is concentrated in the lowest layers, the moving-column model works well. The model is also restricted to a stationary flow pattern since ice thickness is not a prognostic variable but instead used as input to derive the vertical mean horizontal velocity along a flowline.

To date, the most rigorous approach was taken by Jenssen (1977), who tried to solve the thermomechanical equations for "shallow ice flow" [for a more recent and more rigorous definition of shallow ice flow, see Hutter (1983)]. He introduced a scaled vertical coordinate, transformed the relevant continuity and thermodynamic equation (prognostic equations for ice thickness and temperature) and tried to solve the system numerically. In applying the scheme to the Greenland Ice Sheet, however, numerical instabilities occured, forcing the calculations to be interrupted after 1000 years of integration. In the last few years, Hutter et al. (1986) have presented numerical solutions for the steady-state two (vertical plane) dimensional case based on a treatment given by Morland (1984). However, in the paper by Hutter, it appears that numerical problems are still encountered, reducing the applicability of their solution to cases where the basal sliding velocity component has to be far larger than the movement due to internal deformation.

We recently developed a (three-dimensional), fully time-dependent ice sheet model (Huybrechts, 1986) with high resolution in the lower layers (i.e. where the shear concentrates). The inputs of this model are the mass-balance, temperature-dependent flow-law coefficients, the thermal parameters, surface temperature and the basal temperature gradient. We introduced a finite-difference scheme based upon the Alternating-Direction-Implicit method to solve the system numerically. This scheme appears to be stable, relatively efficient and seems to produce very realistic solutions.

Here, we report on some basic sensitivity experiments in which a schematic (East Antarctic) continental flowline is forced with 'glacial/interglacial' climatic conditions (accumulation and surface temperature) and its transient and steady state behaviour investigated. To conclude and assess the role of thermo-mechanical coupling in more realistic situations, the Vostok flowline is modelled. With relevance to the interpretation of the palaeoclimatic signal obtained at Vostok station

(Jouzel et al., 1987), special attention is paid here to a derivation of surface elevation changes following a glacial-interglacial climatic transition.

2. Model description

An elaborate description of the complete ice sheet model and the numerical procedures involved can be found in Huybrechts (1986). Here, only a brief outline will be presented. The numerical gridpoint model used in this paper describes ice flow along a flowline and computes the fully coupled velocity and temperature fields in a two-dimensional vertical plane, while accounting for any flow divergence or convergence in the continuity equation. Since integrating the thermodynamic equation in the computational stage on a grid fixed in space is rather inconvenient, as the upper and lower ice boundaries will generally not coincide with grid-points, a new vertical coordinate ζ, scaled to the local ice thickness, has been introduced. Following Jenssen (1977) this stretched dimensionless vertical coordinate is defined by :

$$\zeta = \frac{H + h - z}{H} \qquad (1)$$

such that $\zeta=0$ at the upper surface and $\zeta=1$ at the base for all values of x and t . In this definition H is ice thickness [m] and h bedrock elevation (zero at sea-level) in the usual Cartesian coordinate system (x,z,t), in which the x-axis is horizontal (x = 0 at the divide) and the z-axis is pointing upwards. The way in which equations are transformed to this non-orthogonal system (x,ζ,t), which will be used below, can be found in e.g. Haltiner (1971). In this approach, velocity and temperature fields are now computed at levels of constant ζ (the layer interfaces). For the experiments discussed in this paper, the vertical domain was subdivided into 10 layers concentrated towards the base with a lowermost gridspacing of $\Delta\zeta=0.02$, which proved to be sufficient to capture the essential characteristics of the model variables.

Ice deformation is assumed to result from shear strain, with the shear stress distribution in the model given by:

$$\tau(\zeta) = -\rho g H \zeta \frac{\partial (H + h)}{\partial x} \qquad (2)$$

where the usual assumptions (sufficiently small bedrock and surface slopes, gridpoint spacings an order of magnitude greater than ice thickness) are used. In this expression g is acceleration of gravity and ρ ice density [910 kgm^{-3}], taken to be constant.

Substituting this equation in a Glen-type flow law with exponent n=3 and integrating the resulting equation with respect to the vertical and using the above coordinate transformation, yields an expression for the horizontal velocity u(ζ):

$$u(\zeta) = 2(\rho g H)^3 H \left[\frac{\partial(H+h)}{\partial x}\right]^2 \frac{\partial(H+h)}{\partial x} \int_1^{\zeta} A(T^*)\, \zeta^3 \, d\zeta + u(1) \qquad (3)$$

with basal boundary condition u(1) = 0.

The flow law coefficient A(T*) introduces the temperature dependence of ice deformation in the model. Apart from factors such as crystal fabric and impurity content, that might be equally important, laboratory experiments suggest that A(T*) obeys an Arrhenius relationship:

$$A(T^*) = m \, . \, a \exp\left[-\frac{Q}{R\,T^*}\right] \qquad (4)$$

In this expression a is specified below, R the universal gas constant [8.314 $Jmol^{-1}K^{-1}$], Q the activation energy for creep, and T* absolute temperature corrected for the dependence of the melting point on pressure ($T^* = T + 8.7\ 10^{-4}\ H\zeta$, with T expressed in K). m is a tuning parameter and proved to be necesssary to slightly adjust the height-to-width ratio in some of the model runs. Its value is generally comprised between 1 and 10 and may be thought of as an implicit way to include the softening effect of crystal fabric and impurity content. Unless indicated otherwise in the text, the following values were chosen for a and Q: $T^* < 263.15$ K, $a = 1.14\ \ 10^{-5}\ Pa^{-3}year^{-1}$, Q = 60 $kJmol^{-1}$; $T^* \geq 263.15$ K, $a = 5.47\ \ 10^{10}\ Pa^{-3}year^{-1}$, Q = 139 $kJmol^{-1}$, so that A(T*) lies within the bounds as put forward by Paterson and Budd (1982).

Vertical motion [in m/year, negative downwards], as a result of accumulation and vertical strain, is calculated from the incompressibility condition, yielding:

$$w(\zeta) = \int_0^{\zeta} \left[H \frac{\partial u}{\partial x}\Big|_{\zeta} + \frac{\partial u}{\partial \zeta} \left\{ \frac{\partial(H+h)}{\partial x} - \zeta \frac{\partial H}{\partial x} \right\} \right] d\zeta + w(0) \qquad (5)$$

with the kinematic boundary condition at the upper surface given by:

$$w(0) = \frac{\partial(H+h)}{\partial t} + u(0)\frac{\partial(H+h)}{\partial x} - M \qquad (6)$$

and M the local mass-balance [m/year], positive in the case of accumulation. Generally, the calculated w at the ice-bedrock interface approached zero (if there is no sliding, the present case) within 0.01 m/year, revealing that the employed scheme conserves mass very well.

In order to adjust the flow-parameter A during the calculation, the temperature distribution within the ice sheet is found from the thermodynamic equation:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p H^2}\frac{\partial^2 T}{\partial \zeta^2} - u\frac{\partial T}{\partial x}\Big|_{\zeta} - \frac{1}{H}\frac{\partial T}{\partial \zeta}\left[\frac{\partial (H+h)}{\partial t} + u\frac{\partial (H+h)}{\partial x} - \zeta\left\{\frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x}\right\} - w\right]$$
$$+ \frac{g}{c_p}\zeta\frac{\partial u}{\partial \zeta}\frac{\partial (H+h)}{\partial x} \qquad (7)$$

Here T is absolute temperature [K], t time [years], k thermal conductivity [6.62 10^7 $Jm^{-1}K^{-1}year^{-1}$] and c_p specific heat capacity [2009 $Jkg^{-1}K^{-1}$]. In this equation heat transfer is considered to result from vertical diffusion (first term), horizontal advection (second term), vertical advection (included in the third term together with the various correction terms accounting for time-dependent layer geometry) and internal deformational heating due to horizontal shear strain rates. Boundary conditions follow from the mean annual air-temperature at the upper surface. At the base, neglecting heat conduction in the bedrock below, the geothermal heat flux is incorporated in the basal temperature gradient, taken to be 2K/100m. This corresponds to a heat flux of 4.2 10^{-2} Wm^{-2}, considered as a value representative for East-Antarctica. Whenever the pressure melting point is reached, temperatures are set equal to that value. At the divide, all horizontal derivatives are zero.

In the model experiments discussed below, also the bedrock response has been taken into account, as the basal temperature distribution turns out to depend critically on total ice thickness. We considered a viscous asthenosphere, with lithosphere deflection following local hydrostatic equilibrium and an ice/mantle rock density ratio of 0.3:

$$\frac{\partial h}{\partial t} = D_a \frac{\partial^2}{\partial x^2}(h - h_0 + 0.3H) \qquad (8)$$

In this expression, h_0 is the undisturbed bedrock topography and D_a [10^8 m^2year^{-1}] a diffusion coefficient. With a typical length scale of 1000 km, this equation leads to a relaxation time for bedrock adjustment of around 10000 years (Oerlemans and Van der Veen, 1984).

Finally, time-dependent evolution of ice thickness is described by:

$$\frac{\partial H}{\partial t} = -\frac{\partial}{\partial x}(HU) - \frac{1}{b}\frac{\partial b}{\partial x}HU + M \qquad (9)$$

with HU the vertically integrated mass flux per unit width given by:

$$HU = H\int_0^1 u(\zeta)\, d\zeta \qquad (10)$$

and b(x) the width distribution along a flowline. In this paper, only 'half' an ice sheet is actually computed, with boundary conditions taken as zero thickness gradient (divide) and prescribed ice thickness at the edge (zero, unless indicated otherwise in the text).

In order to solve (9) numerically, this equation is written as a diffusion equation, with a 'vertically integrated' diffusion coefficient given by the scalar component of (10). We opted for a finite-difference approach, of the type implicit-in-time/central-in-space. A staggered grid in space was employed, in effect calculating mass-fluxes in between grid points with a mean diffusivity. Smoothing in this way turns out to keep the integration stable. The resulting finite-difference equations are usually quite readily solved with an explicit integration scheme. However, such a scheme has the important drawback that in order to preserve stability, time steps necessarily have to be taken small. Alternatively, a semi-implicit scheme, differing from a fully implicit method in that diffusivity is evaluated at the old time step, proved to perform very satisfactorily. Although not unconditionally stable, partly due to strong nonlinear coupling through the source terms, this scheme allows much larger time steps. The resulting tridiagonal linear systems are then easily solved by a Gaussian elimination method.

A comparable approach was taken to solve the thermodynamic equation. Here, the terms involving ζ-derivatives were made implicit, leading once more to a set of tridiagonal equations to be solved at every grid point. However, a note concerning the horizontal advective terms is in order here, as replacing the derivatives by central differences turned out to generate oscillations in the solution. This problem is usually circumvented in diffusion-convection equations with a high Peclet number (i.e. a constant proportional to the ratio of advective velocity and diffusivity) by introducing an artificial horizontal diffusion process (e.g. Mitchell and Griffiths, 1980). We use an 'upwind' differencing scheme that can be shown to introduce an artificial horizontal diffusivity equal to $u.\Delta x/2$, with Δx the grid spacing. Besides stabilizing the integration, this influences results only marginally, as in most cases the associated artificial heat transfer turns out to be an order of magnitude smaller than the horizontal heat advection term. In the experiments discussed here, spatial resolution was chosen to be 50 km. With this value, the flow part allows time steps from 50 up to 100 years, that were also used for the thermodynamic calculations.

3. Basic sensitivity versus environmental conditions

In order to investigate basic sensitivity of a polar ice sheet with respect to environmental conditions (accumulation and sea-level temperature) and to assess the role of the thermo-mechanical coupling, a series of (in first instance) steady state experiments was set up. For this purpose we considered a 'clean' flowline of uniform width, with a flat bedrock profile extending from the ice divide at x=0 to a fixed edge position at x=1500 km. First of all, a reference experiment was defined as follows: mean annual sea-level temperature and atmospheric lapse rate were set at 253 K and 12 K/1000 m respectively. Over the Antarctic Ice Sheet, the accumulation rate appears to be strongly correlated with surface temperature T_S [K],(e.g. Robin and Johnsen, 1983), as the amount of precipitation is limited by the amount of water vapour that can be carried by the atmosphere at any temperature:

$$M = 2.5 \times 2^{\left\{\frac{T_s - 273.15}{10}\right\}} \qquad (11)$$

so that at a surface elevation of 3000 m, M=0.05 m/year, T_S=217 K and at sea-level M=0.625 m/year, respectively. With this parameterisation the mass-balance depends (in climatic change experiments)both on elevation and sea-level temperature.

Initially, computations started with zero ice thickness and bedrock elevation. Depending on the mass-balance, a steady state was usually established after 200000 to 300000 years of integration. With Δx = 50 km, Δt = 50 years and 10 layers in the vertical this required, including graphical output, about 300 CP seconds for every 100000 years and 130000 octal execution field length on a CDC-Cyber 175-750 computer. A realistic height-to-width ratio was obtained by setting m=10 in equation 4.

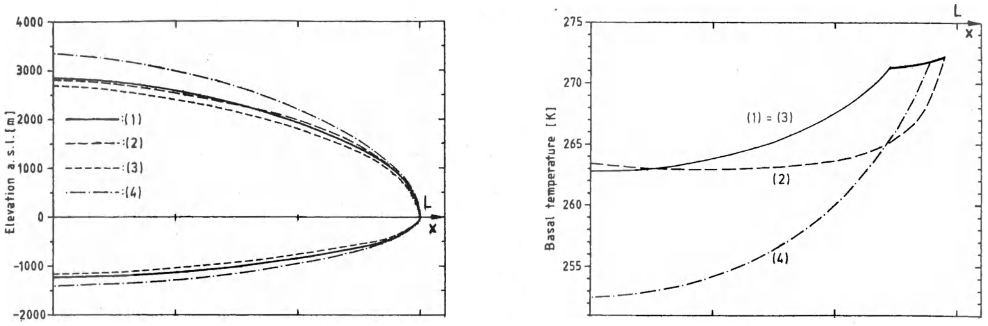

figure1: Steady state ice thickness (left) and basal temperature (right) distribution versus environmental conditions. (1): 'interglacial' reference run with sea-level temp. = 253 K; (2),(3),(4) are for sea-level temp. = 243 K, with (2): accumulation depending on surface temperature (corresponding shift in bed elevation is not shown) ; (3): fixed englacial temperature distribution; (4): fixed accumulation distribution with respect to (1). A thick line refers to pressure melting.

Basic sensitivity of the model to accumulation and/or sea-level temperature changes is displayed in fig.1. Keeping the accumulation distribution fixed with respect to the 253 K reference run (full line) and decreasing sea-level temperature only (point-dashed line), results, not surprisingly, in an increased ice thickness distribution, while the reverse is true for the basal temperatures. The sensitivities found here reflect the combined effect of many competing feedback mechanisms, such as the positive feedback of elevation changes on surface temperature, and the opposing effects of increased ice thickness leading to basal warming, together with the influence due to differences in deformational heat release (although relatively unimportant in this case). The short-dashed line in fig. 1 refers to a sensitivity experiment in which the temperature distribution of the ice sheet was held constant, so in effect showing the effects of changes in accumulation on ice thickness due to ice dynamics only. In this case there exists a negative feedback of accumulation on surface elevation: lower elevations tend to result in increased precipitation rates.

However, in the full-model run, where sea-level temperature, and, accordingly, accumulation rates vary, and full thermo-mechanical coupling is considered, colder conditions (long-dashed line) actually lead to slightly decreased ice thickness in central regions and slightly increased ice thickness in marginal zones, in spite of decreased dissipation and the rather important dependence of ice thickness on changes in surface temperature alone. As the concomitant change in basal temperature in the 'inner half' appears to be quite small, this means that in this particular situation, decreased advection of colder ice towards the basal shear layers associated with the 'glacial' accumulation rates, approximately compensates for the cooling effect of decreased surface temperature. So, generally speaking, the mutual coupling of temperature and velocity seems to have a stabilizing effect on the steady state configuration of a large polar ice sheet like East-Antarctica, submitted to different climatic environments within realistic ranges: the integrated effects of roughly doubling accumulation rates and raising sea-level temperature by 10 K (a typical glacial-interglacial climatic shift) on steady state ice thickness appear to be of similar magnitude, but of opposite sign.

Up to now only steady states were investigated. How these ice sheets actually evolve from one state to another at different locations is a different matter, if one realizes that the various terms in the heat equation all operate on different time-scales. Fig. 2 shows the evolution of ice thickness and basal temperature at 4 locations (labelled in increasing order outwards to the margin) following a linear 10000-year glacial-interglacial temperature rise of 10 K, starting from a steady state 243 K 'glacial' ice sheet (this is the state represented by the long-dashed line in fig.1). Basal temperatures (lower panel) initially increase with higher values downstream, later on counteracted by advection of cooler ice, resulting in a slight basal cooling. After that, temperature rises slightly again, related to the arrival of a strongly diffused 'warm wave', as a result of increased surface temperatures conducted towards the base. Note also that near to the divide (where there is hardly any dissipation) basal layers are actually cooling, as a result of increased vertical advection of cold ice.

The evolution of ice thickness (fig.2, upper panel) follows a somewhat opposite trend. Increased accumulation rates initially lead to increased ice thicknesses. This trend is then reversed as a result of enhanced shear strain due to a warmer base. Eventually, this 'lowering wave' travels upstream and reaches the divide in a much weakened form some 20000 years later. Following these results, it may thus very well be possible that at present, (mainly outer) parts of the Antarctic Ice Sheet are actually lowering as a delayed response on the increased accumulation rates associated with the last interglacial warming. Apparently, dependence of ice deformation on temperature adds a very long time scale to the system. Also, in these experiments no sign was found of runaway behaviour. The dissipation-strain rate feedback seems to be far too weak to give rise to massive basal melting. As demonstrated in Huybrechts and Oerlemans (1988), also the horizontal heat advection term plays a crucial role in damping any runaway temperature increase.

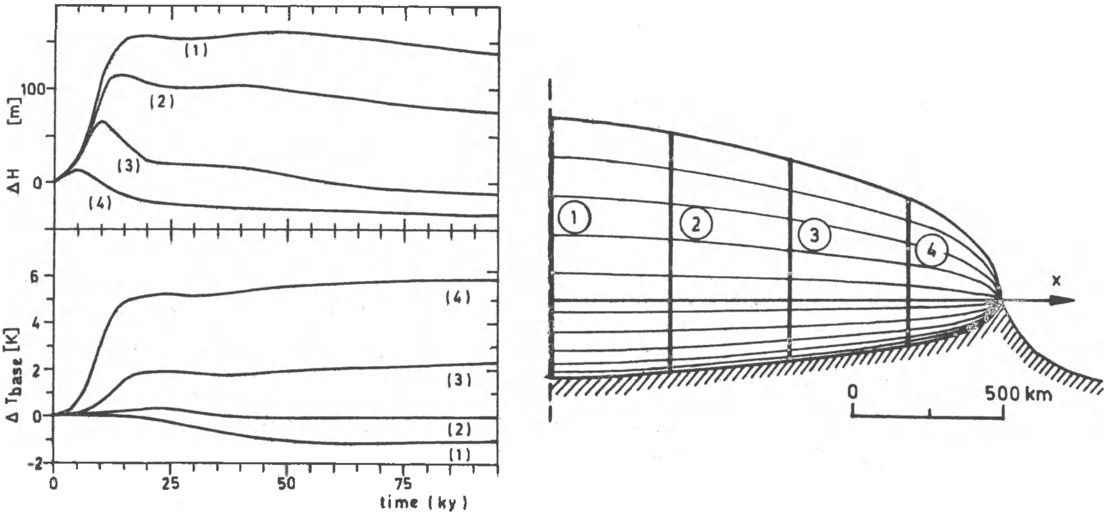

figure 2: Differences in ice thickness (upper panel) and basal temperature (lower panel) following a linear 10K glacial-interglacial climatic shift over 10.000 years starting at t=0. Locations in the ice sheet labelled (1) to (4) are shown to the right.

4. A calculation on the Vostok flowline.

To investigate implications of the thermo-mechanical coupling for the evolution of (a part of) the East Antarctic Ice Sheet with emphasis on the glacial-interglacial contrast, the Vostok flowline was modelled (fig.3). This flowline is of particular interest because local surface elevation changes in the Vostok station area also contribute in the isotope surface temperature signal recovered there (Jouzel et al., 1987), and hence, should be filtered out before a final assessment of these data can be made. Bedrock and surface elevation were digitized on a 50 km-grid along the flowline (of total length 1450 km), taken from the Antarctic glaciological and geophysical folio (Drewry, 1984). Present day accumulation rates (not shown) were taken from a preliminary map produced at SPRI, that also provided a tape with the original accumulation and surface temperature point measurements (Drewry, personal communication). Other parameters for the flowline include: present sea-level temperature = 248K ≈ -25 °C; surface temperature lapse rate = $-0.00875\ \mathrm{Km}^{-1}$; m = 7.

Bed elevation was assumed to be in isostatic equilibrium with present day ice thickness. Fig.3

shows the geometry of the modelled flowline, representing a steady state under present interglacial conditions. Although the experiments conducted so far clearly indicate that the Antarctic Ice Sheet is probably never in a steady state, the tuning parameter m could be chosen (independent on x) such that the modelled surface elevations approached measured surface elevations within 100 meters or less, which we feel proves the validity of the model equations. The Vostok flowline is debouching into the Ross Ice Shelf, where present-day ice thickness (800 m) is a boundary condition. As our present interest is focused towards thermo-mechanical response behaviour, changes in the length of flowlines due to sea-level changes or possible grounding line movement were isolated from the experiments. The corresponding steady state basal temperature distribution during present interglacial conditions is also shown in fig. 3 (lower panel, right). As a general tendency, basal temperatures tend to rise towards the edge (mainly a consequence of increased dissipation) and appear to be strongly controlled by local ice thickness due to the insulating effect of ice.

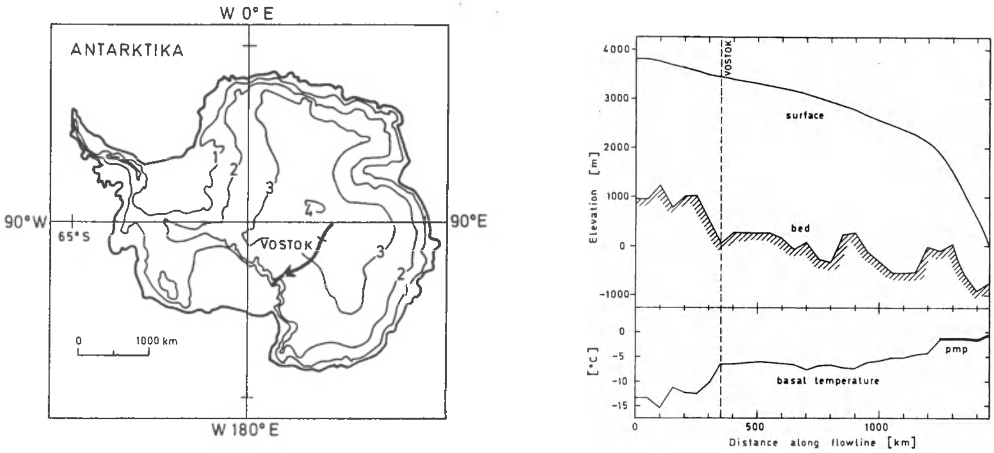

figure 3: Modelled steady state configuration (upper panel) and basal temperature distribution (lower panel) of the Vostok flowline under present interglacial conditions.

In a last experiment, the Vostok flowline was forced with a linear 10K glacial-interglacial sea-level temperature shift over 6000 years, starting from a steady glacial state 16000 years ago (fig.4, upper panel, right), as a general climatic trend deduced from Antarctic ice core data (Robin, 1983). Accumulation rates along the flowline were then calculated as described by Lorius et al. (1985). First, the temperature of formation of precipitation T_f is assumed to be close to the temperature prevailing above the surface inversion layer, leading to (Jouzel and Merlivat, 1984):

$$T_f\,[K] = 0.67\,T_s\,[K] + 88.9 \qquad (12)$$

Then, accumulation rates were calculated from the product of its present value, times the ratio of the derivatives of the saturation vapour pressure over a plane surface of ice (e.g. Kraus, 1972), with respect to T_f for the time of precipitation, and with respect to T_f for present conditions.

$$M\,[T_f(t)] \;=\; M\,[T_f(\text{present})]\,.\,\exp\left\{22.47\left[\frac{T_0}{T_f(\text{present})}-\frac{T_0}{T_f(t)}\right]\right\}\cdot\left\{\frac{T_f(\text{present})}{T_f(t)}\right\}^2 \qquad (13)$$

For surface temperatures prevailing over central Antarctica, this glacial-interglacial temperature shift roughly halves present-day accumulation rates. $T_0 = 273.16$ K is the triple point of water.

Resulting shifts in surface elevation and basal temperature at present (time = 0) and after a final steady state has been established (taking up to 300000 years of integration) are displayed in fig.4. As shown before, the thermo-mechanical coupling adds a very long time scale to the system. As a consequence, a steady state description is quite inappropriate to deduce the present state of the ice sheet with respect to glacial conditions, as is immediately clear from fig.4. At present, surface elevations appear to have risen typically around 100 m in the central area, while the more coastal region appears to have thinned slightly under the influence of a basal temperature increase. This situation compares well with the response behaviour of other East Antarctic flowlines under similar conditions (Huybrechts and Oerlemans, 1988) and is also in agreement with the findings of Lorius et al. (1984), on the basis of total gas content in ice cores.

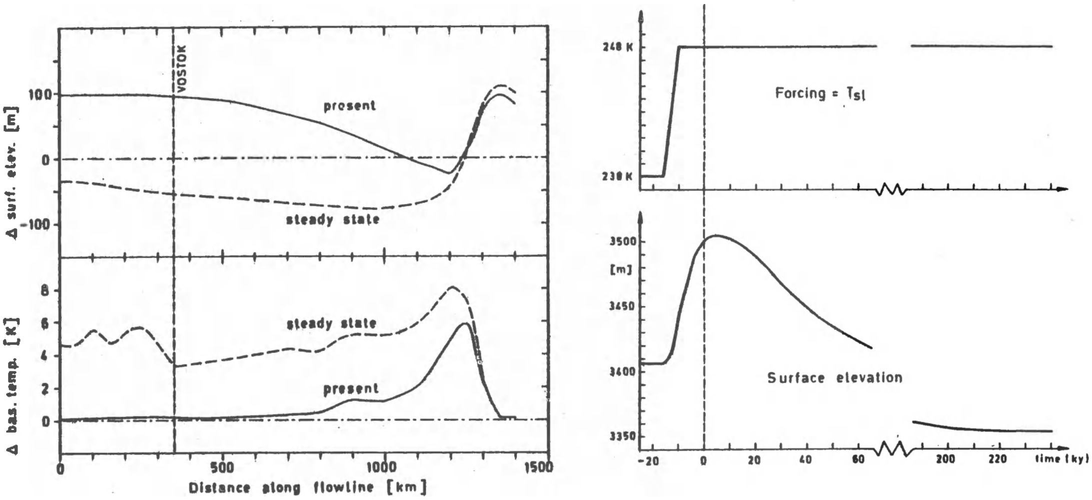

figure 4: Modelled evolution of the Vostok flowline, showing the forcing function (upper panel, right) and differences in surface elevation (upper panel, left) and basal temperature (lower panel, left) at present (time = 0) and after a steady state has been reached. The evolution of surface elevation at Vostok station is shown at the right (lower panel).

In the steady state, on the other hand, changes in surface elevation (amounting to a 0.7 fraction of total ice thickness) indicate a steeper margin and a smaller slope immediately upstream. This results from the warmer base and higher velocities in the outermost area and may also be due in part to a fixed outer boundary condition (where the surface elevation shift is zero, not shown on the graph). The concomitant rise in basal temperature remains below the applied sea-level forcing (10 K).

In central areas, due to the low velocities and the long time-scale connected with diffusion, basal temperatures have at present not shown any response yet and are still at the glacial level. Here again, steady state basal temperature shifts appear to be controlled by local ice thickness, in the sense that the thicker the ice, the more important becomes the cooling effect following increased vertical advection relative to warming due to vertical diffusive conduction effects (fig.4, lower left panel).

A point of particular interest here is Vostok station (fig.4, right), as elevation changes constitute a complicating factor in interpreting the palaeoclimatic signal of the obtained ice core there (Lorius et al., 1985). According to the calculations, the change in elevation since the beginning of the present interglacial 16000 years ago amounts at this moment to about +94 m. The model predicts the surface to rise another 6 m during the next 6000 years, whereafter, if climate were unaltered, it would be lowered by 150 m before setting down to a new steady state. Neglecting a (small) correction related to the origin of ice (deeper ice originated further upstream) and using a fixed atmospheric lapse rate ($-0.00875\ \mathrm{Km}^{-1}$), this calculation indicates that the inferred 16000BP-0BP climatic contrast in the core would be underestimated by about 0.8K due to elevation changes connected with the thermo-mechanical coupling.

5. Concluding remarks

In this study, the response of a continental polar ice sheet to changing climatic conditions was investigated using an efficient numerical model. This model differs mainly from previous models that it computes the mutually interactive temperature and velocity fields and that no a priori assumptions are made regarding their profiles or a steady state. As this model contains enough degrees of freedom and produces relevant boundary conditions, it serves as a 'core' towards the development of a general polar ice sheet model.

With emphasis on the glacial-interglacial climatic transition, our model calculations have shown that the thermo-mechanical coupling has a stabilizing effect on the steady state configuration of a schematic East-Antarctic Ice Sheet. In time-dependent experiments, the model shows a relatively fast response of ice thickness to increased accumulation rates, followed by a lowering trend due to warmer bases that travels slowly upstream. Time scales for this reversal are of the order of 10^3 years in the margins and of 10^4 years in central zones. Also, temperature-dependent creep behaviour of ice appears to add a long time scale to the system, indicating that the Antarctic Ice Sheet is probably never in a steady state.

Modelling the Vostok flowline, indicates that surface elevations near to the ice divide have risen around 100 m since the beginning of the present interglacial, while coastal areas may have thinned slightly. This means that the palaeoclimatic signal obtained at Vostok station is primarily of climatic origin. However, before a final assessment of level fluctuations at Vostok station can be made, the effects of, in particular, heat conduction in the bedrock below and changes in the horizontal model domain should also be looked at in more detail. Recent work by Ritz (1987) suggests that taking into account temperature conduction in the rock below the ice sheet roughly halves the basal temperature response (that would increase elevation shifts). On the other hand, as indicated by Alley and Whillans (1984), grounding-line retreat following a postglacial sea-level rise may have caused significant thinning of central East Antarctica since the Last Glacial Maximum. We intend to study these additional effects in the near future.

The strong dependence of basal temperatures and general climate sensitivity on geometry and topography necessitates the extension of this study to a fully three-dimensional calculation. With present-day supercomputers it is certainly possible to repeat the sensitivity experiments with a 100 km grid for the entire Antarctic Ice Sheet. Such a study is on the way.

Acknowledgement

I thank Hans Oerlemans for his encouragement and very helpful discussions. Philippe Huybrechts is supported by the National Fund for Scientific Research (N.F.W.O.) and in part sponsored by the Belgian Ministry of Science Policy under contract ANTAR/04.

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A SIMULATION OF KATABATIC WINDS IN THE ANTARCTIC COASTAL ZONE

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Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

Keywords Katabatic wind - Sea air interactions - Mesoscale - Ice sheet - Antarctica

Abstract

Katabatic wind, a gravity driven atmospheric flow can be very strong on the steepest slopes of the Antarctic ice sheet, and therefore can maintain coastal water areas free of ice (polynia formation). In these ice free zones, strong heat exchanges occur between the cold atmosphere and the relatively warm ocean, with enhanced sea ice formation and salt rejection in the water column. Ocean - atmosphere interactions in the Antarctic coastal zone are investigated under polar night conditions particularly favorable to katabatic winds development. A mesoscale atmospheric model will be coupled to the different surfaces : sea ice, ocean and ice sheet. The first simulation dealt with the coastal water completely recovered by sea ice and the second one with an open water area extending from the coast to 20 *km* offshore. Although the presence of the polynia does not influence significantly the simulated katabatic flow itself, the heat transfer between atmosphere and ocean is strongly enhanced when ocean is free of ice, which is specially pronounced for the sensible heat flux.

1 Introduction

One purpose of the climate studies done at the Institut d'Astronomie et de Géophysique G. Lemaître is the simulation of long term climatic changes, in particular those characteristic of the last glacial cycle. This study requires to consider the mechanisms driving the climatic system over long time scales, i.e. from a century to a few thousand years. One of these mechanisms, among the most important, is the deep oceanic circulation because it involves large amounts of heat exchanged between the equator and the poles and because the deep ocean is an important reservoir of CO_2. The source of the deep oceanic circulation is localized in ice-free polar oceans. In these zones strong heat transfers occur from ocean to atmosphere,which lead to sea ice formation and salt rejection in the water column. Near the Antarctic coast, this mechanism occurs in wind driven open water areas (polynias). If, particularly during the whole Antarctic winter, the wind is sufficiently strong to advect the new sea ice out of the coastal polynia, the strong ocean - atmosphere heat exchange leads to the formation of dense water which ultimately contributes to the Antarctic bottom water formation.

The aim of the present paper is to simulate such interactions in the Antarctic coastal zone. In particular the heat exchanges between the atmosphere and ice-free ocean will be quantified under strong wind and cold air temperature conditions. Such conditions are observed in Antarctica when either a katabatic wind blows down along the slope of the ice sheet, or cyclonic activity generates easterly storms along the coast, or both. Our study will be restricted to the case of pure katabatic wind events.

In section 2 and 3, the atmospheric and surface models will be described. Section 4 will present the results of two katabatic winds simulations, the first one when the ocean is completely covered by sea ice and the second one when a polynia is present along the coast. Conclusions are drawn in section 5.

2 The atmospheric model

2.1 Equations of the model

The atmosphere is simulated with a mesoscale primitive equations model, assuming homogeneity of the dependant variables along the coast (2-dimensional approximation). To express the surface boundary conditions in a way as easiest as possible, σ-coordinate is used :

$$\sigma = \frac{p - p_t}{p_\star} \qquad (1)$$

where p is the local pressure, p_t is the top fixed pressure of the model, p_s is the surface pressure and $p_\star = p_s - p_t$ is the depth of the modelled atmosphere.

Horizontal equations for momentum are therefore :

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - \dot{\sigma}\frac{\partial u}{\partial \sigma} + f(v - v_g) - \frac{R_a T}{p_\star + \frac{p_t}{\sigma}}\frac{\partial p_\star}{\partial x} - \frac{\partial \phi}{\partial x}\Big|_\sigma + F_x \qquad (2)$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - \dot{\sigma}\frac{\partial v}{\partial \sigma} - f(u - u_g) + F_y \tag{3}$$

where x is the horizontal offshore (positive southward) axis, y is the horizontal onshore (positive eastward) axis, t is time, u, v and $\dot{\sigma}$ are respectively the southward, eastward and σ components of the wind , f is the Coriolis parameter, $\vec{V_g} = (u_g, v_g)$ is the geostrophic wind, R_a is the perfect gas constant for dry air, T is air temperature, $\phi = gz$ is the geopotential, g is gravity, z is altitude, $|_\sigma$ means that the value is calculated on a σ surface. F_x and F_y are the divergences of the turbulent momentum fluxes :

$$F_x = -\frac{\partial}{\partial x}(\overline{u'u'}) - \frac{\partial}{\partial \sigma}(\overline{u'\dot{\sigma}'}) \tag{4}$$

$$F_y = -\frac{\partial}{\partial x}(\overline{u'v'}) - \frac{\partial}{\partial \sigma}(\overline{v'\dot{\sigma}'}) \tag{5}$$

where the overbar indicates time average. It must be pointed out that to preserve simplicity overbar is avoided except for the turbulent fluxes.

The vertical momentum equation is approximated by the hydrostatic equilibrium and after some algebra we get :

$$\frac{\partial \phi}{\partial (\frac{T}{\theta})} = -C_p\theta(1 + .608q) \tag{6}$$

where

$$\theta = T(\frac{p_0}{p})^\kappa \tag{7}$$

is the definition of potential temperature, $p_0 = 1000\ mb$, $\kappa = \frac{R_a}{C_p}$, C_p is the specific heat at constant pressure for dry air and q is the specific humidity.

The equation of state for humid air as a perfect gas is given by :

$$p = \rho R_a T(1 + .608q) \tag{8}$$

The continuity equation is expressed through the time tendency equation for $p_\star$:

$$\frac{\partial p_\star}{\partial t} = -\int_0^1 \frac{\partial (p_\star u)}{\partial x} d\sigma \tag{9}$$

from which $\dot{\sigma}$ can be computed,

$$\dot{\sigma} = \frac{1}{p_\star}[\sigma \int_0^1 \frac{\partial}{\partial x}(p_\star u) d\sigma - \int_0^\sigma \frac{\partial}{\partial x}(p_\star u) d\sigma] \tag{10}$$

The thermodynamic energy equation is :

$$\frac{\partial\theta}{\partial t} = -u\frac{\partial\theta}{\partial x} - \dot{\sigma}\frac{\partial\theta}{\partial\sigma} + \frac{\partial R_{IR}}{\partial\sigma} + F_\theta \tag{11}$$

where R_{IR} is the infrared radiative heat flux (Morcrette, 1984) and

$$F_\theta = -\frac{\partial}{\partial x}(\overline{u'\theta'}) - \frac{\partial}{\partial\sigma}(\overline{\theta'\dot{\sigma}'}) \tag{12}$$

is the divergence of the turbulent heat flux.

The specific humidity conservation is expressed with the following equation :

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - \dot{\sigma}\frac{\partial q}{\partial\sigma} + F_q \tag{13}$$

where

$$F_q = -\frac{\partial}{\partial x}(\overline{u'q'}) - \frac{\partial}{\partial\sigma}(\overline{q'\dot{\sigma}'}) \tag{14}$$

is the divergence of the turbulent moisture flux.

Equations (2), (3), (6), (8)-(11) and (13) form a system of 8 equations for 8 unknows u, v, $\dot{\sigma}$, ϕ, p_*, ρ, θ and q. p and T can be obtained from the definitions (1) and (7) of σ and θ respectively, and the turbulent fluxes introduced in (4), (5), (12) and (14) will be parameterized.

2.2 Upper and lower boundary conditions

The top of the model has been taken at a pressure level $p = p_t$ $(\sigma = 0)$, where the boundary conditions are :

$$\dot{\sigma} = 0 \tag{15}$$

$$\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0 \tag{16}$$

$$\frac{\partial\theta}{\partial z} = 0 \tag{17}$$

$$q = q_{observed} \tag{18}$$

The boundary conditions at the surface $(\sigma = 1)$ are :

$$u, v = 0 \tag{19}$$

$$T = T_s \tag{20}$$

$$q = q_s(T_s) \tag{21}$$

where T_s is the predicted air surface temperature (see below), and q_s is the saturation specific humidity corresponding to the air surface temperature T_s.

2.3 Lateral boundary conditions

Katabatic flow is confined into a thin stable air layer and it perturbs the vertical equilibrium of the atmospheric column. In a stable atmosphere, external gravity waves are generated and propagated in the model and spurious wave reflections can occur at the lateral boundaries. To avoid this problem, the following "radiation" conditions for these waves can be used :

$$\frac{\partial f}{\partial t} + c\frac{\partial f}{\partial x} = 0 \tag{22}$$

where $f = u, v, \theta$ or q and c is the gravity wave velocity. This scheme has been introduced by Orlanski (1976) and discussed later by Miller and Thorpe (1981).

2.4 Parameterization of turbulent fluxes

Turbulence is parameterized by expressing the double covariance term of (4), (5), (12) and (14) by the classical Austausch exchange formulation, and after some algebraic manipulations we get :

$$F_x = \frac{\partial}{\partial x}(K_x\frac{\partial \overline{u}}{\partial x}) + \frac{g^2}{p_\star^2}\frac{\partial}{\partial \sigma}(\rho^2 K_z\frac{\partial \overline{u}}{\partial \sigma}) \tag{23}$$

$$F_y = \frac{\partial}{\partial x}(K_x\frac{\partial \overline{v}}{\partial x}) + \frac{g^2}{p_\star^2}\frac{\partial}{\partial \sigma}(\rho^2 K_z\frac{\partial \overline{v}}{\partial \sigma}) \tag{24}$$

$$F_\theta = \frac{\partial}{\partial x}(K_x\frac{\partial \overline{\theta}}{\partial x}) + \frac{g^2}{p_\star^2}\frac{\partial}{\partial \sigma}(\rho^2 K_{zh}\frac{\partial \overline{\theta}}{\partial \sigma}) \tag{25}$$

$$F_q = \frac{\partial}{\partial x}(K_x\frac{\partial \overline{q}}{\partial x}) + \frac{g^2}{p_\star^2}\frac{\partial}{\partial \sigma}(\rho^2 K_{zh}\frac{\partial \overline{q}}{\partial \sigma}) \tag{26}$$

where the horizontal and vertical turbulent diffusion coefficients are respectively K_x and K_z or K_{zh}. K_x is parameterized following Pielke (1984) :

$$K_x = \alpha(\Delta x)^2[\frac{1}{2}(\frac{\partial \overline{u}}{\partial x})^2 + (\frac{\partial \overline{v}}{\partial x})^2]^{\frac{1}{2}} \tag{27}$$

where Δx is the horizontal grid spacing and α a coefficient which is adjusted until waves that degrade the solutions significantly do not appear.

The parameterizations of K_z and K_{zh} will be different for the surface layer (10 first meters above the surface) and outside. Because the turbulent fluxes in the surface layer may be assumed constant, it is possible to get from the observations a good parameterization of then, although it is computationally expensive. On the other hand, the upper part of the planetary boundary layer is less known but the parameterization of K used in this model is simpler.

2.4.1 Vertical turbulent diffusion in the surface layer

The formulation is given by Businger (1973), who use the friction variables u_*, θ_*, q_* and the Monin-Obukhov length L :

$$u_*^2 = -\overline{V'w'} \tag{28}$$

$$K_z \frac{\partial \overline{u}}{\partial z} = \frac{\overline{u}}{\overline{V}} u_*^2 \tag{29}$$

$$K_z \frac{\partial \overline{v}}{\partial z} = \frac{\overline{v}}{\overline{V}} u_*^2 \tag{30}$$

$$\theta_* = -\frac{\overline{\theta' w'}}{u_*} = \frac{K_{zh}\frac{\partial \overline{\theta}}{\partial z}}{u_*} \tag{31}$$

$$q_* = -\frac{\overline{q' w'}}{u_*} = \frac{K_{zh}\frac{\partial \overline{q}}{\partial z}}{u_*} \tag{32}$$

$$L = -\frac{\overline{\theta} u_*^2}{k g \theta_*} \tag{33}$$

where $k = .4$ is the Von Karman constant, w is the vertical velocity in z coordinates and $V = (u^2 + v^2)^{\frac{1}{2}}$. Using universal functions, and taking into account the roughness length z_0 of the surface, the friction variables are obtained through the values of the corresponding variables at 10 m height, Businger (1973) providing the relationships between $u_{10\ m}$ and u_*, $\Delta q = q_{10\ m} - q_s(T_s)$ and q_*, $\Delta\theta = \theta_{10\ m} - \theta_s$ and θ_*, where θ_s is the potential temperature at the surface. It is therefore possible to use these relations and (28)-(33) in order to determine the contribution of the turbulent diffusions F_x, F_y, F_θ and F_q in the surface layer.

2.4.2 Vertical turbulent diffusion above the surface layer

The parameterization is the following :

$$K_z = l^2 \mid \frac{\Delta \overline{V}}{\Delta z} \mid F(R_i) \tag{34}$$

$$K_{zh} = l^2 \mid \frac{\Delta \overline{V}}{\Delta z} \mid F_h(R_i) \tag{35}$$

where

$$l = \frac{kz}{1 + \frac{kz}{\lambda}}$$

$$\frac{\Delta \overline{V}}{\Delta z} = [(\frac{\partial \overline{u}}{\partial z})^2 + (\frac{\partial \overline{v}}{\partial z})^2]^{\frac{1}{2}}$$

$$R_i = \frac{g}{\overline{\theta}} \frac{\frac{\partial \overline{\theta}}{\partial z}}{(\frac{\Delta \overline{V}}{\Delta z})^2}$$

are the mixing length, the wind shear and the Richardson number respectively. The functions $F(R_i)$ and $F_h(R_i)$ of the Richardson number are given by Louis (1979).

2.5 The grid and the numerical scheme of the model

Horizontal grid spacing is regular : $\Delta x = 20\ km$. Vertical discretization is irregular to get more σ-levels near the surface. The initial height of the first σ-level is the anemometer level $z = 10\ m$. The time step is such that the Courant-Friedrich-Levy criterium is being hold for fast gravity waves. Hence $\Delta t = 40\ sec$ was adopted. The numerical scheme is based on splitting techniques (Bornstein, 1975 and Gadd, 1978). The horizontal mesoscale pressure gradient is computed on an isobaric surface to avoid errors originating from the small difference between the 4^{th} and 5^{th} terms of the right-hand side of equation (2) because they are large and have opposite signs. The contribution of the pressure gradient to the first horizontal momentum equation is achieved with a leap frog scheme. For the turbulent flux contributions a semi-implicit scheme is used and for advection a semi-lagrangian scheme.

3 The surface model

In this section, the simulation of the surface temperature T_s is described for each type of surface, especially for the ice sheet and for the sea ice. If open water areas appear in the model, their surface temperature are fixed at the freezing point $T = 271.2\ K$.

3.1 The ice sheet surface model

The energy balance at the ice sheet surface is computed, using the Deardorff (1978) model

$$\frac{\partial T_s}{\partial t} = -C_1 \frac{H_A}{\rho_s c_s d_1} - C_2 \frac{T_s - T_2}{\tau_1} \tag{36}$$

with $C_1 = 3.72$, $C_2 = 7.4$, H_A (positive upward) is the sum of the heat fluxes coming from the atmosphere and absorbed at the ice sheet surface : the solar and the net infrared radiative fluxes, the sensible and latent heat turbulent fluxes. The surface parameters for the ice sheet are those of the compacted snow : the specific mass : $\rho_s = 330\ kg\ m^{-3}$, the heat capacity : $c_s = 2\ 10^3\ kg^{-1}\ K^{-1}$, the thermal diffusivity : $\kappa_s = .27\ 10^{-6}\ m^2\ sec^{-1}$, the depth reached by the diurnal temperature wave : $d_1 = (\kappa_s \tau_1)^{\frac{1}{2}} = .15\ m$, with the length of the day : $\tau_1 = 86400\ sec$. Finally T_2 is the mean air surface temperature and is assumed to be the average of T_s over the previous 24 h.

3.2 The sea ice surface model

The energy balance at the sea ice surface is also computed using the Deardorff (1978) model. Numerical values of the sea ice surface parameters are those of the compacted snow, which is assumed to cover the sea ice during the Antarctic winter.

Table I: Initial atmospheric profiles for the katabatic winds simulations

altitude z (m)	pressure p (mb)	temperature T (K)	relative humidity U (%)
0.0	1000.0	250.0	63.
709.2	907.6	250.0	83.
1182.0	850.8	250.0	97.
2046.0	756.0	250.0	86.
2622.0	698.6	250.0	78.
3100.6	654.2	247.3	80.
5015.0	499.0	236.5	86.
8371.0	299.8	213.6	13.
10849.0	200.3	206.4	23.
15067.0	99.0	202.5	20.

4 Simulation of katabatic winds

For studying the sensitivity of the model to the ocean - atmosphere interactions in the Antarctic coastal zone, two simulations have been done with polar night conditions : the first one with the ocean near the coast completely covered by sea ice and the second one with a prescribed size polynia located between the coastline and 20 km offshore.

4.1 Input of the simulations

The altitude z_{surf} of the ice sheet surface in the model is chosen to be parabolic and is fitted to the topography of Antarctica near Mirny :

$$\begin{aligned} z_{surf} &= 2800.0\ m\ \sqrt{\frac{x}{3.5\times10^{5}\ m}} &&,\ 350\ km > x > 0 \\ z_{surf} &= 2800.0\ m &&,\ 350\ km < x \end{aligned} \tag{37}$$

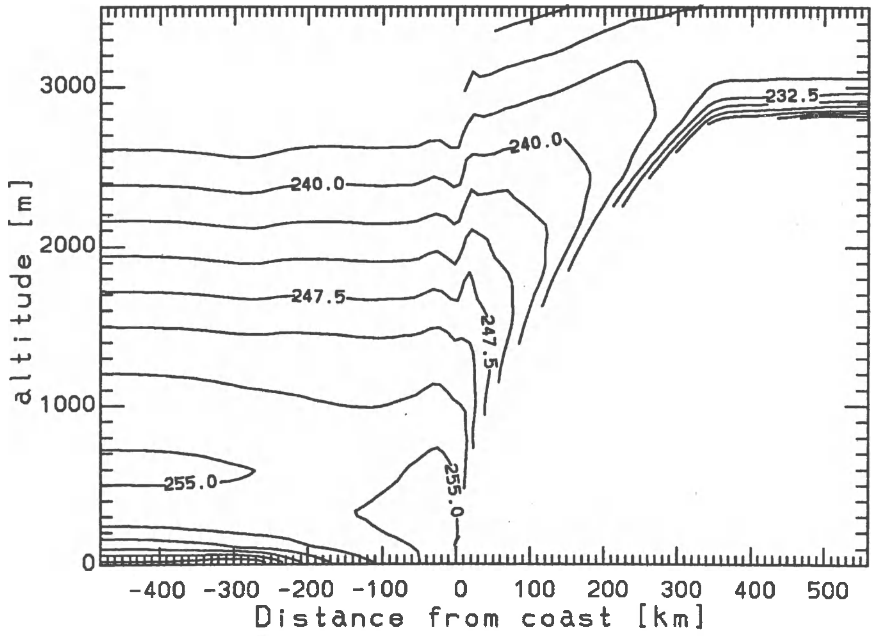

Figure 1: *The temperature field in a plane perpendicular to the coast. Contour interval of* 2.5 *K*

where x is measured inland from the coast. The lateral boundaries are fixed respectively over sea and inland at 480 *km* and 560 *km* from the coast. Initial temperature and humidity vertical profiles are the same for both simulations and are interpolated on σ-levels from data given in table I, between the surface and the top pressure $p_t = 500\ mb$. The upper parts of these profiles, i.e. above $p = p_t$, are fixed and are used for infrared radiative fluxes computations. The zonally averaged mean winter observed conditions at 67° *South* (see Oort, 1983) were modified to get an isothermal profile from the level $T = 250\ K$ to the surface. Initial wind speed has been set equal to its geostrophic value, which is chosen to be $\vec{V_g} = (0, 0)$ at all levels for both simulations. For simulation 1, the type of surface is only snow which covers both the sea ice and the ice sheet. The roughness lengh of snow is chosen to be $z_0 = 0.01\ m$. For simulation 2, the first offshore ocean grid point is assumed free of ice, and there $z_0 = 0.001\ m$.

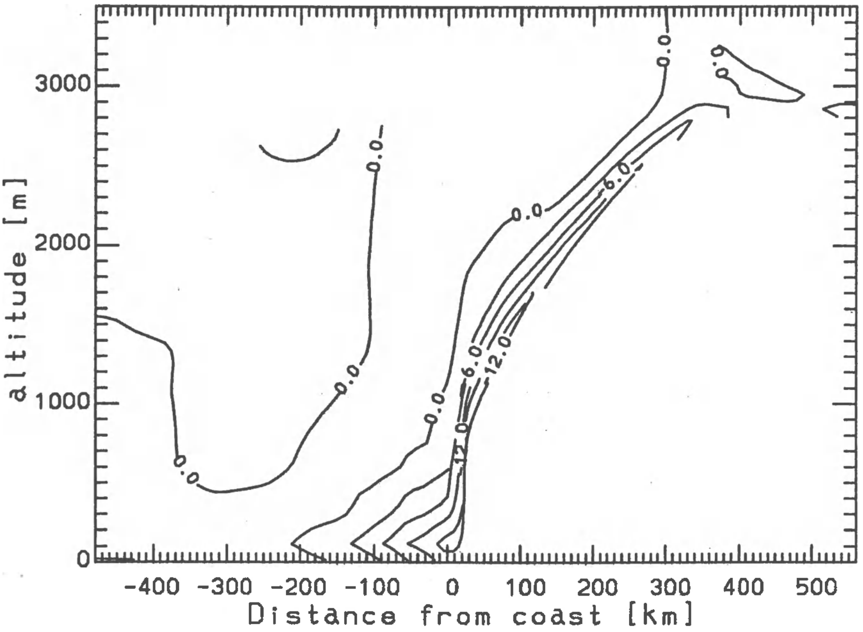

Figure 2: *The u component of wind field in a vertical plane perpendicular to the coast. Positive values indicate that wind direction is Southward. Contour interval of 3.* $m.sec^{-1}$. *Note that the wind on the slope of the ice sheet has negative values.*

4.2 Results of both simulations

Each simulation was run for 6 days, to get a thermodynamic equilibrium between the downward and upward radiative heat fluxes at the top p_t of the dynamical model. The results shown here are those obtained at the end of the simulations. The results of simulation 2 serve as reference and the differences between both simulations will be given when appropriate.

4.2.1 The simulated temperature field

The simulated temperature field over the whole model domain, i.e. in the (x, z) plane, is plotted on figure 1 for simulation 2. The temperature inversion near the surface results from the radiative cooling due to the high surface albedo of Antarctica. The minimum temperature is localized on the Antarctic plateau. The model simulates

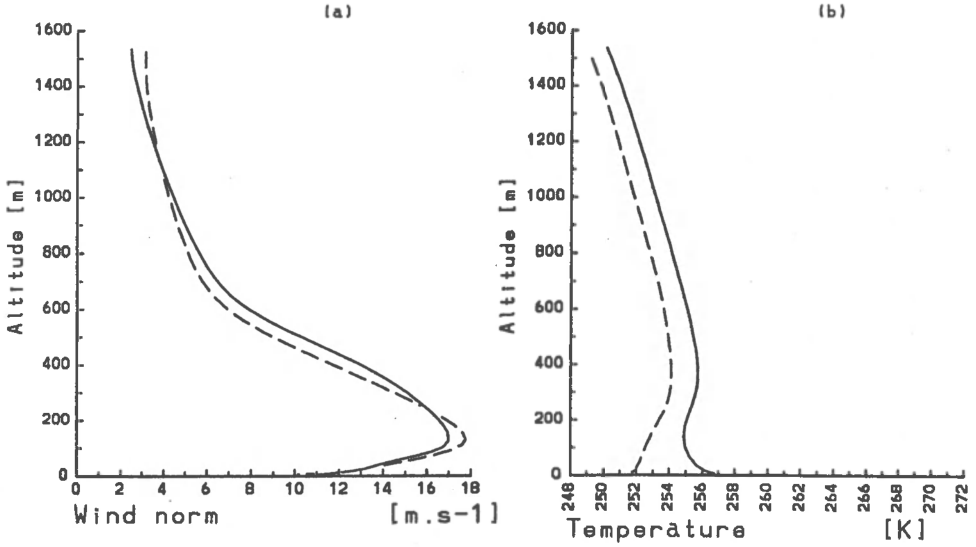

Figure 3: ***Vertical simulated profiles of (a) wind speed norm and (b) temperature, over the first coastal ocean grid point. Dashed lines are related to simulation 1 (without coastal polynia) and full lines to simulation 2 (with a coastal polynia)***

also a maximum temperature in the katabatic layer, near the coast. This is due to the adiabatic compression of the descending air. Figure 3 b shows the vertical temperature profile at the coast for both simulations. The top of the inversion is not far from the height of 200 m, in good agreement with the observations at Syowa (Adachi, 1979, his figures 2 - 5). The warming of the air column due to the presence of the polynia is also noticeable.

4.2.2 The simulated wind field

The figure 2 shows the component u of the wind perpendicular to the coast. The gravity driven downward acceleration of the flow along the slope of the ice sheet is clearly seen. u reaches an extremum not far from the bottom of the ice sheet and speed decreases rapidly after the breaking of the slope. At 10 m height, the u component of the wind for the coastal ocean grid point A is $-10\ m\ sec^{-1}$, which is still sufficient to maintain there an ice free oceanic surface, even during winter (see Pease, 1987). The vertical simulated profile of the wind speed V at grid point A for both simulations has also been plotted on figure 3 a. The maximum wind is 17 $m\ sec^{-1}$ at roughly 150 m heigh, which is also in good agreement with the observations of Adachi (1979). In fact the katabatic flow affects only a very thin layer above the surface of the slope. But the model simulates a deepening of this layer with the slowing down of the katabatic wind when it penetrates over the sea. This last feature was also observed during the IAGO [1] campain which took place during the Austral summer 1985-1986 (André, 1987). A comparison between the vertical profiles of u and v over the coastal ocean grid point A for simulations 1 and 2 is shown in figures 4 a and b. Both show the wind vectors turning left from the steepest slope direction, because of the Coriolis deflection. When a polynia is formed, the lower roughness of the water causes the turbulent fluxes to increase the wind in the surface layer, resulting in a faster v component for simulation 2. This is a low level jet whose existence seems to be proved by the observations (see Schwerdtfeger, 1984) but which needs further studies using better roughness lengths characteristics of the Antarctic ice sheet, ocean and sea ice, and higher horizontal resolution.

4.2.3 The vertical heat fluxes

Table II gives a comparaison between simulation 1 and 2 for the heat fluxes in the surface layer at the coast. When ocean is free of ice (simulation 2), the sensible heat transfer from the ocean to the atmosphere is large. This is due to the strength of the wind ($V_{10m} = 12\ m\ sec^{-1}$ at the coast) and to the temperature difference between the cold air and the warm ocean (15 K). The latent heat flux increase from simulation 1 to 2 is less important because of the low saturated water vapor pressure in Antarctica. The total heat loss per unit area from the polynia is 825 $W\ m^{-2}$. During the Antarctic winter, the water column near the coast is roughly at the freezing point (Zwally et al, 1985). Therefore, the only way to remove heat from the ocean is by ice formation. It means that this simulated heat loss of 825 $W\ m^{-2}$ corresponds to a sea ice formation

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[1] IAGO : Interaction - Atmosphère - Glace - Océan

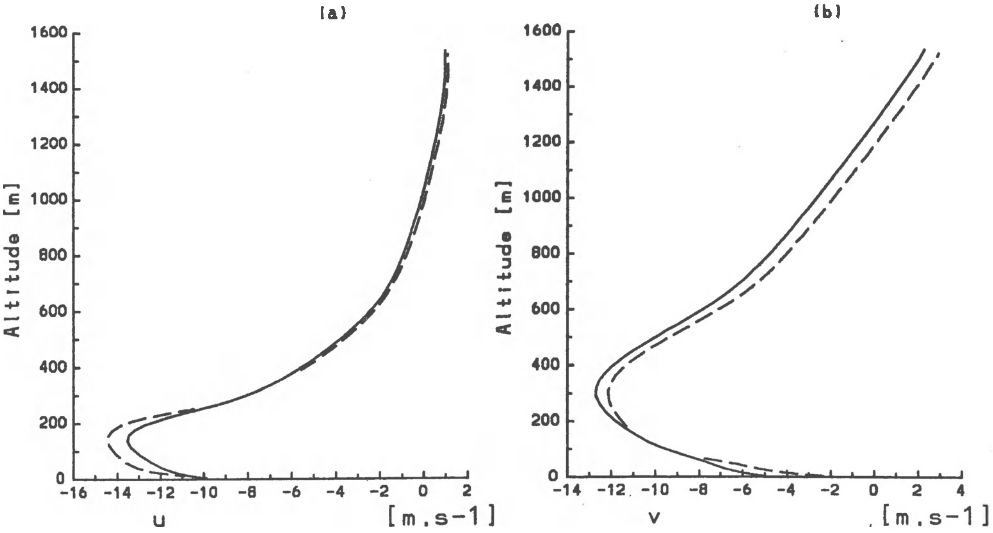

Figure 4: *Vertical simulated profiles of (a) the u component of the wind (positive Southward) and (b) the v component of the wind (positive Eastward), over the first coastal ocean grid point. Dashed lines are related to simulation 1 (without coastal polynia) and full lines to simulation 2 (with a coastal polynia).*

at a rate of .22 *m* per day. It is relevant to point out that the polynia remains because the large wind speed pushes away from the coast the sea ice as soon as it is formed. These are realistic values already observed for the Terra Nova Bay polynia (Kurtz and Bromwich, 1985).

5 Conclusions

Katabatic wind is a noticeable atmospheric phenomenon, especially in Antarctica, where the conditions required for its onset are present during most of the year. Its impact on the atmosphere-ocean interactions in the polar regions of the Southern Hemisphere must be emphasized because the strength of the wind is sufficient to maintain the ocean free of ice in the Antarctic coastal zone. The simulations of katabatic winds presented in this study are in good agreement with available obser-

Table II: Vertical heat fluxes in the coastal surface layer (positive upward)

$W.m^{-2}$	simulation 1	simulation 2
net I.R.	97.	156.
sensible	-89.	526.
latent	16.	143.
total	24.	825.

vations. They show the importance of the atmosphere - ocean heat exchanges when the water is free of ice : the increase of the sensible heat transfer to the cold atmosphere is indeed particularly significant. The resulting sea ice formation is important and through the offshore advection by the wind of the new sea ice, it can generate a large salt rejection in Antarctic coastal water.

Acknowledgments

The authors wish to thank Prof. J.Neumann and P.Alpert for providing us with an initial version of the mesoscale atmospheric model, and for stimulating comments and suggestions during their visits to the Institut d'Astronomie et de Géophysique G. Lemaître in Louvain-la-Neuve. We also thank Prof. J.Cl.André and Dr. P.Pettré for useful discussions at the Centre National de la Recherche Météorologique, Toulouse, France. The following text presents results of the Belgian Program "Scientific research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsability is assumed by its authors.

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III. CONCLUSIONS AND PERSPECTIVES

MARINE ECOLOGY AND GEOCHEMISTRY

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One of the most striking characteristics of the Southern Ocean ecosytem, quite noticeable even for the occasional observer, is the surprizingly high abundance of macroorganisms, which provides a paradoxical impression of "richness". This impression partly originates from the pecular structure of the higher trophic levels of the Antarctic ecosystem. While in temperate aquatic systems, the individual size of organisms generally increases by about one order of magnitude for each increase of one level in the food web, the jump of size is of three orders of magnitude for each trophic level in the Antarctic food chain linking phytoplankton, krill and whales (see Fig. 1). This means that very large organisms occupy trophic positions where we "used" to see much smaller ones. Even when taking into account the trophic position of organisms, however, the biomass of consumers still appears surprizingly high, with respect to the mean biomass of primary producers, sothat it is difficult to explain, according to the standards derived from our knowledge of temperate marine systems, how these high biomasses can be sustained on the production of organic matter occuring in the Southern Ocean.

Understanding this paradox is obviously a prerequisite for a rational management of the marine living resources of the Southern Ocean. None of the Belgian teams taking part to the Belgian Antarctic Research Program have directly tackled this problem. The work of the four teams involved in marine ecology and geochemistry can however basically be resituated within this general problematics, which it approaches from downstream, i.e. from the point of view of the ecophysiology of the first trophic levels and of the oceanological processes controlling them. In this account, I try to underline and discuss the commun conclusions reached by these different teams in so far as they are leading to a better understanding of the overall structure and function of the Southern Ocean ecosystem.

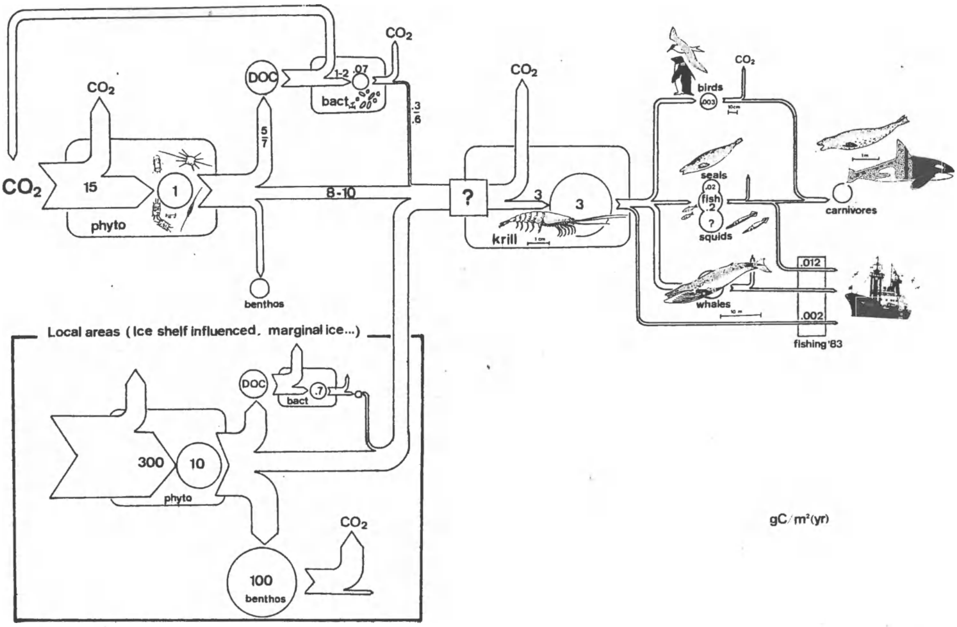

Figure 1. Diagrammatic representation of the food web structure and carbon circulation in the Antarctic marine ecosystem. The figures given must be considered as indicative only. (Data from SCAR, 1983).

A fist commun observation is the extreme variability in the temporal and geographical distribution of the living resources of the Southern ocean. This was also underlined by a recent seminar held in Paris by the CCAMLR and the IOC. This variability seriously complicates the establishment of ecological budgets at the scale of the Southern Ocean, and requires to multiply observations at several sites and periods. From this point of view, the fact that two Belgian teams could visit the same area at two different periods of the Austral summer (the VUB and ULg teams on board of the RV Marion Dufresne sampled in mid January some stations North of Prydz Bay that were revisited one month later by the ULB team, on board of the MV Nella Dan) was of invaluable usefullness for the interpretation of their observations: in their paper, Billen et al shows that consideration of the seasonal variations of bacterial activity allows to reconcile contradictory statements published in the literature concerning phytoplankton-bacteria relationships in Antarctic waters.

Apart from causing methodological difficulties to the observer, the temporal and geographical variability of the Southern Ocean appears as a basic characteristics of this ecosystem, which deeply influences the whole organization of the trophic web. In this context, Lancelot et al showed that primary production in the Antarctic Ocean is by nature generally low but can locally and temporarily reach very high values.

The control of primary production by hydrodynamical processes was shown at two very different scales. Based both on local observations and on physiological modelling, Lancelot et al showed the role of vertical mixing of the water column in determining phytoplankton biomass and production. Based on data collected during large scale transects, Hecq and Goffart showed the role of general oceanic circulation patterns in the geographical distribution of phyto- and zooplankton. Both studies calls for a better cooperation between biologists and hydrodynamicists. A comprehensive model of primary production should indeed result from the coupling between physiological models in the line of that developped by Lancelot et al and physical models able to predict and characterize the hydrodynamical processes determining the vertical mixing of the upper layer of the water column at local scale on the one hand, and the circulation of the water masses at large geographical scale on the other hand.

Concerning the latter aspect, a promising approach is that proposed by Dehairs and Goeyens, consisting of identifying the different water masses involved in the horizontal and vertical pericontinental circulation by aid of geochemical tracers. Their results suggest that, beside the classical oceanographical variables (temperature, salinity, oxygen and nutrients concentrations), elements like Barium can be usefull indicators for understanding the large scale processes of formation and circulation of specific water types.

These indicators, however, are far from being inert and conservative tracers. As for most of the elements in the biosphere, their distribution is also strongly influenced by biological activity, sothat in the same time as the study of Barium distribution can bring some light into processes of importance for marine ecology, the knowledge of ecological processes are also of importance for understanding Barium distribution.

This is only one example showing the importance of <u>understanding at a rather fine physiological level the basic processes linked to biological activity in the Antarctic Ocean</u>. Only by such a refined approach can the ecological characteristics of the Southern Ocean with respect to temperate systems be recognized and understood. Among these basic processes succeptible to deeply differ in Antarctica and in other marine areas, the mechanisms of reserve storage constitute a clue to the understanding of the ecophysiology of phytoplankton and zooplankton, as underlined by both Lancelot <u>et al</u> and Hecq and Goffart. The processes of reserve storage are also of importance in the understanding of the contamination of marine organisms by organochlorine derivatives, which seems surprizingly not negligeable after the results obtained by Joiris <u>et al</u>. Indeed, whatever the mechanisms leading to contamination of living organisms by these toxicants can be (adsorption, partition, food chain transfer, elimination,...), the internal stocks and the physiological turnover of the different metabolites to which they can bind (lipids particularly) must exert a strong control on the levels they reach.

As seen, in spite of the diversity of the questions addressed and the technical means deployed, the work performed within the Belgian Antarctic Research Program in the field of marine ecology and geochemistry present a firm coherence. The perspectives it opens for a better understanding of the function of the Antarctic ecosystem are promising. Of course, however, the final objective of this research, i.e. a comprehensive model of the dynamics of the marine resources of the Southern Ocean, will only be nearing completion through international cooperation. This cooperation is already largely initiated, since close scientific exchanges occured between Belgian and Australian, French, German and British scientists. It will be developped in the next future, namely at the European level in the framework of the EPOS Program. The living resources of the Southern Ocean are generally considered among the possible resources of Antarctica as those which lend themselves the best to economic exploitation. Exploitation of the Krill already began and could very rapidly expand. The example of the near complete disappearance of seals from all accessible sites following intensive hunting in the late 18th and early 19th centuries, that of the extinction of most big cetaceans in the Southern Ocean following the development of industrial whaling in the early 20th century illustrate the fragility of the Antarctic marine ecosystem when submitted to uncontrolled exploitation. Only through the continuation of internationally coordinated research efforts could the challenge of a rational management of the marine resources be taken up.

GLACIOLOGY AND CLIMATOLOGY

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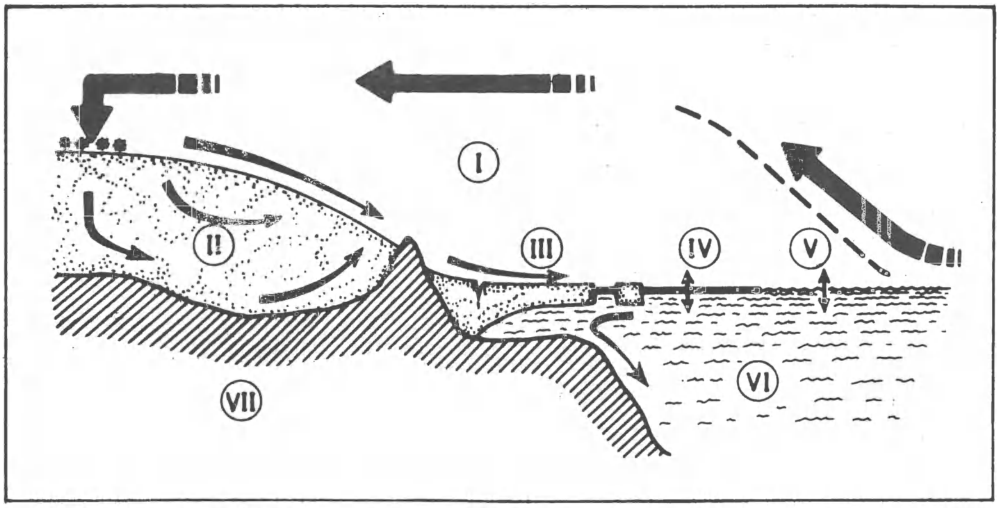
The roots of the present "Antarctic Glacial System" can be traced back to Eocene and Oligocene times, a geological period characterized by the drifting apart of Australia and South America from Antarctica. The separation resulted in a strong oceanic circulation around Antarctica triggering a gradual glacierization of the whole continent. This configuration of a huge ice loaded continent, surrounded by sea, formed since then a relative stable system (as compared to northern hemisphere ice sheets) and has been instrumental in the creation of Late Cenozoic and Present global climates.
However, the existence of a so called "permanent" Antarctic Ice Cap can be seriously questioned today. Variations did occur and because of the interaction of the ice cap with atmosphere and oceans and its capability of locking more than 90 % of the global fresh water reservoir, the study of the system seems to be fundamental in understanding the past behaviour of the earth's environment and varying ocean levels. By extrapolation this will also apply for the future climatic conditions especially when it comes to possible human advertent and inadvertent modification.

The Antarctic Glacial System consists of different easily recognizable subsystems : the atmosphere subsystem (I) ; the ice cap subsystem (II) ; the ice shelf subsystem (III) ; the sea ice subsystem (IV) ; the open ocean subsystem (V) ; the deep ocean subsystem (VI) ; the lithosphere subsystem (VII).
Although each of them can be studied seperately, understanding their interrelation, will open the gate towards a true "geophysical" model of the Antarctic System, which is ultimately needed if one wants to understand the significance of this particular glacial system for the global environment.

The most variable part is the atmospheric subsystem (I). Notwithstanding this variability a mean meridional circulation picture emerges with uplifting of moist air in the cyclones and along frontal disturbances, surrounding the Antarctic plateau, and subsequent poleward displacement. Over the glacial highland subsidence prevails associated with outward flowing surface wind, the so called katabatic wind, moving down the ice slopes as a consequence of gravity and radiational cooling. This fundamental return system has been succesfully modelled by H. Gallée (Institut d'Astronomie et de Géophysique G. Lemaître, UCL). The outward flowing system is important as an element in the mass balance of the ice sheet and ice shelves. Also, locally, its divergence and convergence helps to explain the distribution of blue ice areas. In particular it is being studied by the UCL group in its relation to the existence of polynyas and open water leads within the pack ice area off the coastal zone and the energy fluxes between atmosphere and ocean.



The circumpolar ocean around Antarcica helped the ice sheet to develop. The Antarctic ocean with the conspicuous Ross Sea and Weddell Sea embayments create a typical oceanic circulation system with great influence on the seasonal varying pack ice distribution and the drift of the many ice-bergs. A 2-D model for the ocean circulation, driven by the known wind field and ocean tides, was developed by J. Berlamont, M. Fettweis and I. Hermans (Laboratorium voor Hydraulica, KUL). It was applied to an area covering more or less the Atlantic part of the Southern Ocean, including the Drake Passage, and concentrating -with a refined grid- on the Weddell Sea. The model simulates the observed circulations very well and the efficient computer implementation allows it among other things to be used on a PC for operational purposes.

Subsystem (IV) is the area of the Antarctic ocean covered by sea ice. It is characterized by a very large seasonal variation, from 16 106 km2 at the end of the winter to 2,5 106 km2 at the end of the summer. Therefore, most of the ice is less than 1 year old with a mean thickness of 1-1,5 m. At its outer boundary -a large circumference around 60°S- the sea ice interacts, unconstrained by land masses, with the open ocean and cyclone storms. The mere existence of this pack ice influences fundamentally the energy exchange between atmosphere and ocean. Its modelling is therefore of utmost importance in understanding the impact of the Antarctic glacial system. Cl Demuth and J.P. Van Ypersele de Strihou (Unité de Gestion du Modèle Mathematique Mer du Nord et Estuaire de l'Escaut, Brussels) have developed a model based on the thermodynamic processes as well on the dynamical components of the system, i.e. wind stress and ocean currents. The most interesting result seems to be the simulation of a large polynya in the Weddell sea gyre close to where it is actually often observed.

Subsystem (II) is the "hard core" of the Antarctic Glacial System. It consists of a huge ice sheet, in West Antarctica predominantly marine based while in East Antarctica the ice floor is generally well above sea level. The dynamics of this East Antarctic Ice Sheet are being studied by H. Decleir, Ph. Huybrechts and L. De Vos (Geografisch Instituut, VUB). Ph. Huybrechts developed a time dependent 3-D ice sheet model which computes the fully coupled velocity and temperature field and the distribution of mass. Basic sensitivity experiments along flow lines show the overall stabilizing effect on the steady state configuration due to this mutual coupling of temperature and deformation. Also, an interesting and complex response to a climatic transition can be observed caused by the different time scales on which temperature and stress field react. Because of the screening effect of such a large ice cap on the underlying bedrock, direct observational evidence of the dynamics of the ice cap are restricted to the few isolated mointain areas. H. Decleir and L. De Vos participated during the austral summer 1986-87 in a Japanese expedition (JARE 28) to the Sør Rondane Mountains, Dronning Maud Land. In this marginal mountain area they measured ice thickness profiles and deformational characteristics of the outlet glaciers which will help to explain the observed glacio-geologic phenomena related to ice cap variations.

Another way to find out more about the dynamics of the ice cap is by sampling the ice and investigating its physical and chemical composition. R. Souchez and J.L. Tison (Laboratoire de Géomorphologie, ULB) developed a model for the determinations of the freezing rate by means of the isotope composition of the ice (DHO, $H_2{}^{18}O$). Since the Deuterium content can be measured to a high accuracy, sampling of successive thin ice layers allows the prediction of the freezing rate. The model was tested both in the laboratory and on lake ice in Belgium. Application of the method is now under way by studying sea ice cores of Breid Bay (Dronning Maud Land) while numerous samples are expected to be obtained during the 1987-88 austral summer due to a participation of J.L. Tison in the coming 1987-88 British Antarctic Survey (UK) Expedition. The study of the freezing rate is helpful in understanding the processes during accretion of ice at the bottom of ice shelves and in unravelling the gliding mechanism -related to the pressure melting regelation mechanism- of ice at the ice /rock interface.

This symposium showed that an important number of the scientific achievements pertaining to glaciology and climatology within this program were made in the field of modelling. In addition, most of the subsystems have been succesfully modelled by young scientists in a relatively short time span (2 years). Some of the models show -from a numeric-technical point of view- great similarities, all of them present openings towards mutual interaction. It is clear that each of them can be incorporated in a more complex system, ultimately in a geophysical model with global implications. As it stands now such systems will only be achieved in an international and multi-disciplinary cooperation and the Belgian scientific community is ready for it.

To day the rapid progress of the modelling exceeds by far the observational evidence necessary to test and validate the theoretical findings. This is not unexpected. Antarctic logistics and hazard present an enormous obstacle, only to be surmounted at the expense of high cost and much field experience. Thanks to the generous offer of the Japanese Antarctic Research expedition one Belgian Group was able to operate in remote areas close to the antarctic-plateau. Another Group is now (austral summer 1987-88) in the field at the invitation of the British Antarctic Survey. Here also -like in modelling- success will continue to depend on the international platform. However the vast geophysically unexplored territories in Antarctica and the hope for a scientific rich harvest when drilling to bedrock in Antarctica will be achieved justifies the continuing effort.

CLOSING ADDRESS

Alain STENMANS
Secretary General of the Science Policy Office
Chairman of the Colloquium

Mesdames et Messieurs,

C'est pour moi un honneur et un plaisir de m'adresser à vous à l'issue de cette Journée d'Etudes.

En premier lieu, je tiens à remercier toutes les personnes présentes pour leur participation à cette Journée d'Etudes et en particulier tous les orateurs qui nous ont présenté avec autant de clarté cette matière si complexe. Mes remerciements s'adressent tout spécialement à nos hôtes étrangers qui, par la présentation des activités menées dans leurs pays, ont permis à la fois de situer notre action dans un contexte international, et d'élargir les perspectives de nos chercheurs. A cette occasion j'ai également à coeur de les remercier d'avoir offert aux chercheurs belges la possibilité d'utiliser leurs moyens logistiques et leurs équipements scientifiques en vue de réaliser les indispensables études in situ. Je souhaite profondément que ces collaborations puissent se poursuivre et s'intensifier dans le futur.

Les différentes communications présentées aujourd'hui démontrent que les conditions sont réunies pour aboutir à la concrétisation des objectifs du programme, soit, d'une part, au plan international, contribuer à améliorer la connaissance scientifique de l'Antarctique, et d'autre part, au plan national, développer des méthodologies scientifiques d'intérêt plus direct pour la Belgique.

Au niveau international, la Belgique occupe à nouveau une place parmi les pays actifs dans le domaine de la recherche scientifique sur l'Antarctique même si celle-ci est encore relativement modeste. L'intégration d'équipes belges dans les expéditions d'autres pays membres du Traité sur l'Antarctique a abouti à la mise en oeuvre de collaborations internationales pluridisciplinaires qui sont nécessaires pour mener à bien les recherches en Antarctique.

Les exposés et les interventions dont nous avons pu prendre connaissance à l'occasion de cette Journée d'Etudes, et notamment les exposés relatifs aux conclusions et perspectives, témoignent qu'au terme d'une période de 2 années seulement, des progrès significatifs, bien qu'ils soient encore loin de constituer un corps de connaissances complet, ont pu être enregistrés dans les domaines précis abordés par le programme.

Deze fragmentaire kennis omtrent het Zuidpoolgebied laat zeker nog niet toe met autoriteit adviezen te verstrekken of besluiten te formuleren om een optimaal beheer van het milieu en van de hulpbronnen van dit gebied te garanderen. Evenmin volstaat de kennis om de impact van dit gebied op wereldniveau in te schatten. Vele vragen blijven vooralsnog onbeantwoord. Denken wij hierbij maar aan de invloed van het klimaat op de evolutie van de ijskap en vice-versa, de gevolgen van deze interrelatie op het zeespiegelniveau, de werking van de voedselketen en de mogelijkheden tot visserij of de gevaren van overbevissing, de aanwezigheid van niet hernieuwbare hulpbronnen en de beperkingen of voorzorgen die moeten genomen worden voor hun eventuele exploitatie.

Het is eenieder duidelijk dat het onderzoek nog een lange weg heeft af te leggen en de meest aangewezen weg hiertoe blijkt de internationale samenwerking te zijn. Ik stel bijgevolg met vreugde vast dat er een Europees intitiatief is tot stand gekomen namelijk het "Network on Polar Science" onder de auspiciën van de "European Science Foundation" om de samenwerking inzake poolonderzoek te bevorderen. In deze context hoop ik ook tenvolle op een verlenging van de huidige Belgische inspanning met als drieledig doel :

a) de verderzetting van de versteviging van de expertise nodig voor België om op significante wijze aanwezig te zijn in de wetenschappelijke activiteiten ontwikkeld in het kader van het Antarctisch Verdragsysteem;

b) een verruimde bijdrage te leveren tot de wetenschappelijke kennis die de basis vormt voor het rationeel beheer van het leefmilieu en de natuurlijke hulpbronnen van Antarctica enerzijds en voor het inschatten voor onze planeet van de invloeden van dit continent op het klimaat, de circulatie van de oceanen en de atmosferische gesteldheid anderzijds;

c) ontwikkeling van methoden en wetenschappelijke concepten die mogelijk van toepassing zijn voor wetenschappelijke vraagstukken met concreet belang voor België.

Tenslotte rest mij enkel nog de eer U te mogen uitnodigen op de receptie die ik ter afsluiting van deze Studiedag kan aanbieden.

Pour terminer, il me reste encore le plaisir de vous inviter à la réception qui clôturera cette Journée d'Etudes.

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