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Foreword

The Southern Ocean constitutes the world's largest ecosystem. It is dominated by krill, one species of which (Euphausia superba) may be the most abundant animal species on earth (with man being the second). Krill are the principal food of fish, squid, penguins, other seabirds, seals, and whales. One of the distinctive features of this ecosystem is that warm blooded animals are the main carnivores. Both the fate of the whales and the possibility of large-scale fishing of krill are factors that are now driving biological investigations in this region.

To consider these matters, the Antarctic Treaty Nations and the Intergovernmental Oceanographic Commission requested the Scientific Committee on Antarctic Research to convene an International Conference on Living Resources of the Southern Ocean. This Conference was hosted by the National Academy of Sciences in 1976 with support from the National Science Foundation. Subsequently, with agreement on the need for sound management of the Southern Ocean ecosystem, the Antarctic Treaty Nations in 1980 developed a Convention on the Conservation of Antarctic Marine Living Resources. This Convention is unique in requiring an ecosystem approach to fishery management.

The present report reviews the ecosystem approach to the conservation problem, with special attention to krill, and recommends the elements of a U.S. research effort. This effort is envisaged as a contribution to international undertakings, especially the program of Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS), which is jointly sponsored by the Scientific Committee on Antarctic Research, the Scientific Committee on Oceanic Research, and the International Association of Biological Oceanography of the International Council of Scientific Unions, and the Advisory Committee on Marine Resources Research of the Food and Agricultural Organization of the United Nations. This undertaking has special relevance in helping to provide the scientific basis required for implementation of the Marine Living Resources Convention.

The report was prepared for, and supported by, the National Science Foundation, the National Oceanic and Atmospheric Administration, and the Marine Mammal Commission.

The Ocean Sciences Board and the Polar Research Board express their indebtedness to John H. Steele, Chairman of the Committee to Evaluate Antarctic Marine Ecosystem Research, and to other members of his Committee for their dedication and efficient work in preparing the report.

A. L. Washburn
Chairman
Polar Research Board

Warren S. Wooster
Chairman
Ocean Sciences Board

Preface

The study culminating in this report was undertaken at the request of the National Science Foundation, the National Oceanic and Atmospheric Administration, and the Marine Mammal Commission.

The Polar Research Board and the Ocean Sciences Board were assigned responsibility for evaluating the U.S. Antarctic marine ecosystem research program and appointed a joint *ad hoc* Committee to Evaluate Antarctic Marine Ecosystem Research in the spring of 1980. The Committee's terms of reference are to:

1. Evaluate national and international plans for marine ecological studies in the Antarctic in relation to U.S. scientific interests;

2. Recommend appropriate targets for U.S. contribution to Antarctic marine ecosystems research;

3. Examine the national and international management structure for BIOMASS and make suggestions to interested U.S. agencies as appropriate.

The Committee met three times in 1980, (1) to review past, present, and planned Antarctic marine ecosystem research; (2) to assess state-of-the-art acoustic techniques, satellite remote-sensing capabilities, and moored arrays that might have application to marine ecosystem research in the Antarctic; and (3) to consider U.S. national and international interest in the Antarctic and discussion of linkage of the Committee's scientific and technical recommendations to the management structure within the U.S. Government.

A final meeting and workshop was held in April 1981 to complete the report and to stimulate and initiate planning of two coherent (defined as coordinated multidisciplinary programs with several principal investigators and several years of support) research programs to understand (1) the basis for krill aggregation and (2) the biological and physical processes involving the marine ecosystem at and near the pack-ice edge.

The members of this Committee wish to thank all the participants in our meetings. Their valuable contributions to the discussions are the basis on which this report is based. We are pleased to acknowledge the assistance provided by the Polar Research Board. The Committee, and especially the Chairman, are very grateful to the Executive Secretary, W. Timothy Hushen, not only for the smooth running of all our meetings but for his own contributions to our discussions and particularly for his significant role in the preparation of this report.

John H. Steele, Chairman
Committee to Evaluate Antarctic
Marine Ecosystem Research

Contents

1 Summary and Recommendations

GENERAL

Summary

The United States has major interests in, and commitments to, Antarctic marine ecology. These include:

1. The role of the United States as one of the Antarctic Treaty nations.

2. Participation of the United States in the International Whaling Commission.

3. Commitment of the United States to the new Convention on Conservation of Antarctic Living Resources.

4. U.S. interest in potential exploitation of mineral and hydrocarbon resources in the Antarctic.

5. Scientific study of Antarctic marine ecosystems as a major contribution to our general knowledge of marine ecology.

6. U.S. interests in the long-term status of marine mammal, bird, and other populations.

Investigations of the Antarctic marine ecosystem are inherently international, but it is recognized that U.S. interests in the region are not necessarily identical with those of other countries. Unlike several other Antarctic Treaty members, there is no direct U.S. interest now in harvesting living resources. However, there is significant U.S. involvement with the conservation of several species directly or indirectly affected by such exploitation. Further, there is great concern over the potential environmental impact of possible hydrocarbon exploitation in this region. The major instrument currently for international collaboration in Antarctic marine ecosystem research is the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) Program, sponsored by the Scientific Committee on Antarctic Research (SCAR) in cooperation with the Scientific Committee on Oceanic Research (SCOR), the International Association of Biological Oceanography (IABO), and the Advisory Committee on Marine Resources Research (ACMRR) of the United Nations Food and Agricultural Organization, but there are numerous other international organizations with interests in Antarctic marine ecology (see Appendix B). The national and international activities in this region range from basic studies to commercial exploitation of resources. The Committee has taken account of this wide range of interest and believes that U.S. scientific effort in field programs can be made more effective by a careful selection of topics.

We find that scientific problems can be identified that are central to an understanding of Antarctic marine ecosystems and directly relevant to the questions of management and conservation and to the goals of BIOMASS. These problems are amenable to study at realistic levels of support.

Recommendations

The United States should have a strong long-term program in Antarctic biological oceanography, because of the great intrinsic interest in this region and its renewable and nonrenewable resources.

The United States should support the general aims of BIOMASS and contribute to its goals. The U.S. contributions should complement those of other countries by drawing on U.S. strengths in marine research.

A selection of topics should be given special emphasis as research programs. The criteria for selection should be (a) quality of the science, (b) relevance to resource and conservation aspects, and (c) international commitment/cooperation.

The U.S. program in Antarctic marine ecosystem research should be structured to include (a) coherent programs, (b) special studies, and (c) individual projects.

Resource, conservation, and political needs give rise to targeted research activities. While these activities are selected on the basis of relevance to resource and conservation aims, the research within these targets must be judged on the basis of scientific quality.

Remote sensing, moored instruments, drifting buoys, and towed samplers all have the potential to provide biological data in new forms and with increased efficiency. Future equipment design and construction should be specifically aimed at their use in this region. Provision for adequate calibration and intercomparison is required. The use of acoustic measurements is especially important. Future program planning should be based on the use of these techniques and instruments.

Over the longer term, we believe that U.S. plans must include the construction of a new ice-strengthened vessel or vessels. At the least, and as an interim solution only, a smaller ship (150-180 ft), specifically for research in the ice, should be made available.

SCIENTIFIC RESEARCH NEEDS

Topics for research should be considered in three categories: (a) coherent programs, described as coordinated multidisciplinary research programs involving several investigators and requiring several years of support; (b) special science projects to deal with certain critical questions; and (c) individual research.

The Committee identified the following coherent programs, which it considers deserve special attention and which fit within the general aims of BIOMASS:

Coherent Projects

1. The physical, chemical, and behavioral processes underlying the formation and persistence of krill aggregations should be studied because of their great ecological interest. An understanding of these processes is essential for management of any krill harvest so as to assure maintenance and improvement in whale stocks. This work should build on the strength of the U.S. program in Antarctic physical oceanography.

2. Processes in and near the ice pack during seasonal formation and retreat of the ice edge should be studied. This is a special environment important to many species of birds and mammals and to stages of krill development that could be of great significance for their overall life cycle. Further, this ecosystem could be most seriously affected by proposals for development of nonrenewable resources.

The Committee sponsored workshops to develop research plans for these programs. Reports of these workshops are included as Appendixes E.1 and E.2.

Special Projects

Certain gaps in knowledge of the Antarctic ecosystems that limit our overall assessment of krill dynamics would be aided by appropriate experimental studies. More studies should be made on the populations and feeding biology of squid and pelagic fish because of their critical roles as predators. Research on these questions and the development of the necessary techniques should be encouraged.

Individual Research

Favorable consideration should be given to any proposal containing new ideas for studies in Antarctic marine ecosystem research. New investigators, especially, should be encouraged to propose and pursue research on these ecosystems.

Interdisciplinary Planning

In all stages of planning and execution, the physical and biological components of field studies should be viewed as closely linked joint programs requiring the best efforts of interested scientists. Such joint planning of further Antarctic marine programs should be an essential requirement for all future work. Within the context of studies of the large-scale features, there should be advantages to both disciplines in collaborative studies that clarify mesoscale physics and fine structure and elucidate the relation of these features to biology.

Conclusions regarding research on specific components of the ecosystem are given in the body of the text.

NATIONAL AND INTERNATIONAL MANAGEMENT
(See Chapter 7)

Summary

The Antarctic Treaty established a politically unique framework for control of the region based on the concept of peaceful use. Preservation of the aims of this Treaty is a prime U.S. objective.

Questions of exploitation of renewable and nonrenewable resources--key issues not covered in the original Treaty--have introduced vital new elements into the national and international management of research (and of funding) for the marine ecosystems in the Antarctic.

We recognize that an exact balance in interests between basic science and resource-oriented studies is not practically possible.

Recommendations

In terms of national management involving several agencies, specific program aims should be defined initially in the context of separate priorities for marine ecological research, resource management, and conservation.

Based on management objectives of the National Science Foundation (NSF), the quality of science should have priority in defining the research objectives for field programs supported by NSF in the Antarctic.

Targeted research programs that arise from the political and social awareness of conservation and resource needs should be selected on the basis of relevance to these needs as determined by the relevant agencies.

Implementation of these separate aims, through field programs, data analysis, and evaluation, will demand integration of efforts at sea and in the laboratory between scientists from many organizations, academic and federal. It is essential that, as these different aims are realized in specific projects, the planning and execution be carried out with the closest collaboration among the various organizations. This collaboration is especially desirable because the great cost of logistics of field operation demands the utmost efficiency.

BIOMASS has strong support in several countries with major Antarctic interests, and the United States should continue to develop an Antarctic marine biological research program within this framework. General approval of the aims of BIOMASS is not inconsistent with special directions for

U.S. studies, therefore the United States should develop its own scientific programs within this structure.

The United States should join in supporting, through SCAR, an international BIOMASS secretariat, which should be relatively small and attached to a program of Antarctic studies.

STEERING COMMITTEE FOR ANTARCTIC MARINE ECOSYSTEM RESEARCH (AMER)

Conclusion: To meet the needs of BIOMASS and other international activities, and to advise on the integration of programs of the relevant agencies, a continuing committee should be established consisting of scientists representing the physical, biological, and technological programs currently under way or envisaged in academic and federal institutions.

FUNDING (See Chapter 8)

Logistic costs are a dominant element in the budget for Antarctic activities, being far greater than the science component of the budget. It is necessary to ensure that the essential science costs are protected from the effects of inflation on logistics.

The expected cost of the programs outlined here will be in the range of $6 million to $9 million per year excluding ship support.

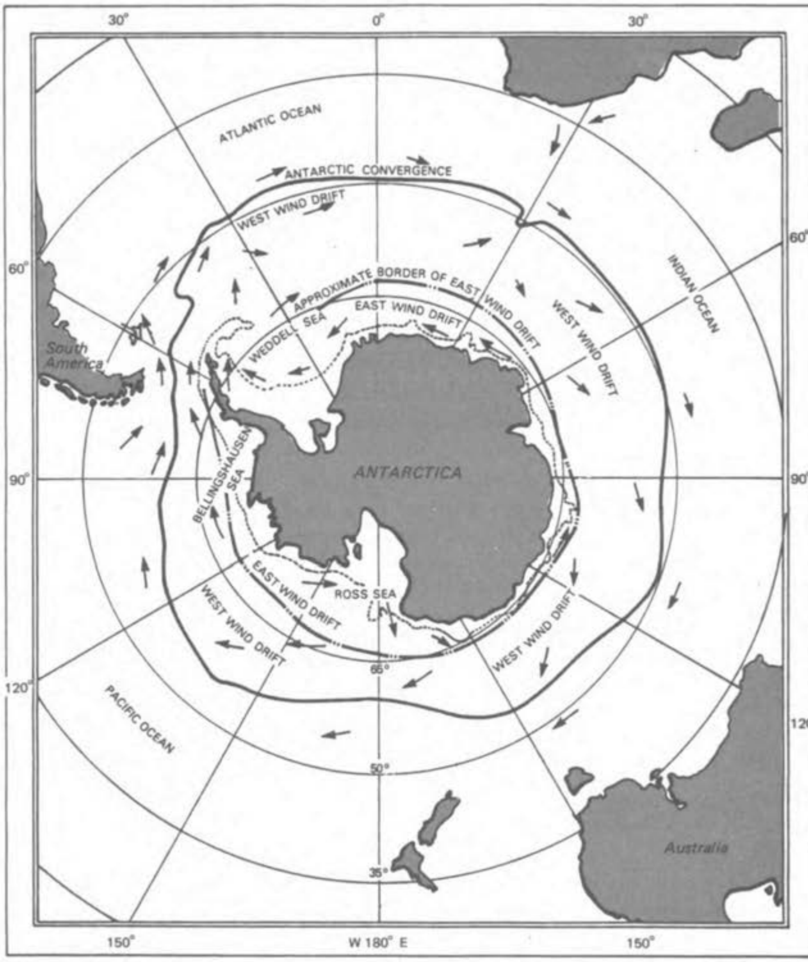


FIGURE 1 Major Southern Ocean Current Systems.

2
Introduction

The Antarctic continent covers about 14 million square kilometers, an area larger than the United States and Mexico. The ocean south of the Antarctic Convergence is about 10% of the world oceans and contains the largest ocean current system (Figure 1). It has a dominant effect on global circulation and on ocean mixing. Within these waters and around the edges there are diverse and productive ecosystems that have fascinated explorers and scientists and have been subjected to severe exploitation. We recognize the Southern Ocean as a region having a certain physical and ecological coherence requiring study in its entirety if we are to comprehend the dynamics of its water movements and its populations. But the very size of the area with which we are concerned imposes limitations on our research. It is apparent that any realistic Southern Ocean field program cannot be truly comprehensive and must select topics and regions within which to carry out research. Further, for biological studies, we are involved in a complicated mixture of issues.

The general concern with conservation has focused on marine mammals as a critical issue and especially on the whale species, which spend part of their lives feeding in the Antarctic. This concern for marine mammals overrides strictly economic evaluations and in turn is related to questions about commercial exploitation of the whale's main food source, krill. Looming behind these immediate issues is the potential exploitation of the mineral resources and the consequent need to define methods for environmental protection. A committee of SCAR (Zumberge, 1979) has reviewed this aspect and emphasized the need for more information on the ecosystem, particularly near the edge of the continental shelf. All of these factors contribute to the desire for more studies of the Antarctic marine ecosystem, but there is also the intrinsic fascination of this system as an object for basic research that can deepen and broaden our understanding of ocean biology. These aspects, in the long term, should be seen as the basis on which to build an integrated field program, but there is also a need to be selective in relating methods of study to issues.

The relative remoteness and "hostility" of the Antarctic seas exacerbate the problem of carrying out research. Recent studies of the physical environment have depended on new shipboard instruments with fast rates of data collection in the sea, but especially on the use of subsurface moored instrumentation and on drifting buoys linked to satellites. A major need in biological research is to develop a similar approach by combining improved ship-deployed instruments with moored systems and with remote sensing. This aspect has been given special attention by the Committee.

Investigations of the Antarctic marine ecosystem are inherently international, but we should recognize that U.S. interests in the region are not identical with those of other countries. Unlike several other Antarctic Treaty members, there is no immediate U.S. interest in harvesting living resources. However, there is significant U.S. concern with the conservation of several species directly or indirectly affected by such exploitation.

International collaboration has been an essential element in the development of policy, of regulation, and of scientific study. There is a long tradition of marine research in the Antarctic, beginning with the Discovery Investigations; more recently the International Southern Ocean Studies (ISOS) program has carried out intensive studies of the physical environment. The Antarctic Treaty Nations at their eighth meeting in Oslo in 1975, recognizing the developing pressures of possible living resource exploitation, requested SCAR to convene a meeting to review the question of the living resources of the southern ocean. From this meeting arose the international program, Biological Investigation of Marine Antarctic Systems and Stocks (BIOMASS). The previous work forms an essential basis for planning and provides the evidence for evaluation of further research directions. The BIOMASS proposals (El-Sayed, 1977, 1981) display the great range of questions that can be asked about the Antarctic marine ecosystem. It is apparent that, for individual national programs, some choices must be made to emphasize certain features of the total system and complementary approaches encouraged for different national programs.

We consider that scientific problems can be identified that are central to an understanding of Antarctic marine ecosystems; that are directly relevant to the questions of management, conservation, and the goals of BIOMASS; and that are amenable to study at projected levels of support.

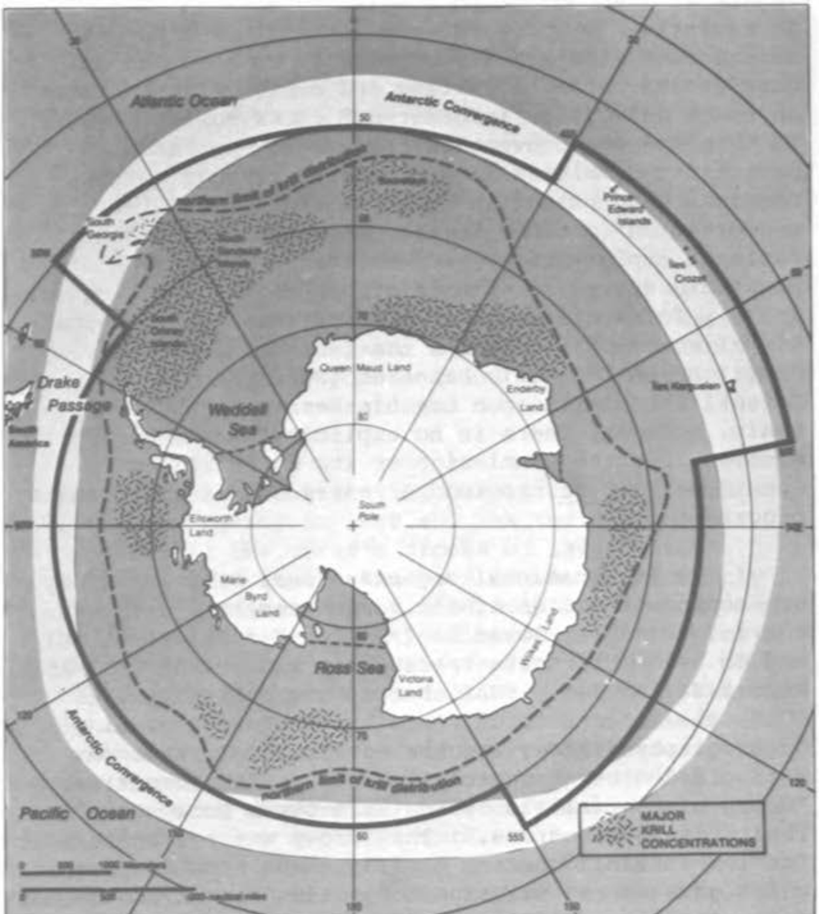
3
National and International Activities

G. Hempel defines the three motives for BIOMASS as "Science, Resource Development and Ethics" (BIOMASS Report #6). In various combinations these underlie the concern of the many international organizations involved in the Antarctic.

The International Whaling Commission (IWC) was established by treaty in 1948 and has the responsibility of managing the world's stocks of large whales. Baleen whales feed in the Southern Ocean, particularly on krill. The IWC was established to balance exploitation and conservation (by nations harvesting the great whales). In its early years the desires of those seeking exploitation predominated; more recently there has been a much stronger emphasis placed on conservation, with a great deal of pressure from international conservation organizations and from groups ethically opposed to modern commercial whaling. Many other organizations have a declared interest in this topic; for example, IUCN (International Union for the Conservation of Nature and Natural Resources) sponsors studies of the possible effect of krill harvesting on whale stocks. The Intergovernmental Oceanographic Commission (IOC) has been asked to facilitate international data exchange. These organizations do not conduct field programs but depend on data from commercial operations or from other research studies, although field programs can be planned under their auspices.

The Antarctic Treaty nations have formulated a "Convention on the Conservation of Antarctic Marine Living Resources," May 1980, which will come into force after ratification by 8 of the 15 signatories. The area encompassed by the Convention is shown in Figure 2. The Convention states, inter alia, that "it is essential to increase knowledge of the Antarctic marine ecosystem and its components so as to be able to base decisions on harvesting and conservation measures on sound scientific information" (SCAR Bulletin #67). To this end the Convention intends to appoint a Scientific Committee as a consultative body to the Commission to establish criteria and methods for conservation (defined in the Convention as including rational exploitation); assess status and trends of populations; assess effects of proposed harvesting (of krill); formulate proposals for national and international research; work with the IWC, the Scientific Committee on Antarctic Research (SCAR), and the Scientific Committee on Oceanic Research (SCOR). Again, however, there is no explicit intent, at present, for the Commission or its Scientific Committee, per se, to fund or carry out field research programs.

The international organizations, SCAR and SCOR, are component bodies of the nongovernmental structure, the International Council of Scientific Unions (ICSU), and do not participate in resource management (BIOMASS Report Series #1). SCAR, has in cosponsorship with SCOR, the International Association of Biological Oceanography (IABO), and the Advisory Committee on Marine Resources Research (ACMRR), an FAO committee, a "Group of Specialists on Southern Ocean Ecosystems and Their Living Resources." This Group was responsible for the initial document outlining the BIOMASS program, which gave as its principal objective "to gain a deeper understanding of the structure and dynamic functioning of the Antarctic marine ecosystem as a basis for the future management of potential living resources." The Group stated that it "would be willing to provide advice for governments if so requested" (BIOMASS Report Series #1).



National Science Foundation

FIGURE 2 Boundary of Marine Living Resources Convention (Heavy Line).

This brief history of the international structure is intended to display some of the mixture of motives for BIOMASS as defined by Hempel. All are commendable, and their integration is desirable. But it must be recognized that each objective may give a different emphasis to field programs and cause different criteria to be used in evaluating such programs. Thus the nature of U.S. involvement depends on the relative weight given to each objective and can differ from those of other countries taking part in BIOMASS. Particularly, the United States is not involved, nor is it likely to be involved, in commercial harvesting of whales, krill, or fish in the Antarctic. The main direct commitment has been to physical and biological studies funded through the NSF. This does not preclude concern with the management of economic and noneconomic resources but can indicate a different emphasis within the wide range of studies proposed by the various international entities.

The general aim of "understanding the Antarctic marine ecosystem" is necessarily long term, possibly Utopian. Thus any particular program must select certain of the overall objectives. Such a program should be internally coherent in its scientific aims but should also be viewed in terms of the international effort. The needs of resource management tend to focus on estimates of the total stocks of whales, krill, and seals, for example, and to construct large-scale surveys that can provide this information. From this perspective, it is recognized that smaller-scale studies are an important, if secondary, aim. On the other hand, these smaller-scale processes may provide the scientific links between our interpretation of events in the Antarctic and in other regions such as the Gulf Stream or subtropical upwelling areas where there are closely related U.S. programs in biological and physical oceanography.

The dichotomy between resource and process-scale studies is only one way of selecting topics, but it may provide a means for focusing U.S. scientific interests in the Antarctic. To provide a more specific evaluation requires a consideration of recent work in the marine regions of the Antarctic and general developments in biological oceanography.

4
Synopsis of Recent Research

There are many excellent reviews of Antarctic marine research (Bengston, 1978, is a primary source). The purpose of this chapter is not to duplicate these but to highlight particular points relevant to the aims of the report. Thus the following notes are certainly selective and probably biased. Their purpose is to suggest directions for future research within the relevant U.S. scientific community.

PHYSICS

The mean, large-scale features of the circulation and property distributions south of the Antarctic Convergence or the Antarctic Polar Front have been relatively well known for some years (Committee on Polar Research, 1974). A general eastward circulation over most of the region results from the westerly wind regime; the band of easterly winds near Antarctica together with the irregular shape of the continent and bathymetric effects combine to produce a series of clockwise circulation gyres. The southern boundaries of these gyres lie near the coasts of Antarctica. The northern boundaries between the gyres and the main eastward flow of the Antarctic Circumpolar Current (ACC), at least in the case of the Weddell Gyre, are complex hydrographically and are also areas of great interest biologically, since they may serve to circumscribe populations of some species.

Recent studies have focused on and emphasized the spatial and temporal variability of currents and water-mass regimes in the ACC system. Observations within the Drake Passage have shown the existence of three "fronts," separating different water masses. The central front is usually called the Antarctic Polar Front or, historically, the Antarctic Convergence. These fronts are also cores of eastward, geostrophic flow. This same general pattern of zonation of the current and water masses has been confirmed by observational studies south of Australia/New Zealand and of South Africa.

The fronts or current cores of the ACC are known to migrate laterally and to form wavelike disturbances. These disturbances frequently close on themselves, forming current rings or eddies. In the Drake Passage region, typical eddy diameters are 80 to 100 km; south of New Zealand, they may be 2 to 3 times larger. These eddies may form on either side of any front, and they represent mechanisms for the potential redistribution of large amounts of heat, salt, nutrients, marine life, and other properties. Such eddies may pass a given geographical position within a few days to weeks but have lifetimes of several months to years. Accurate estimates of net fluxes require averaging over a number of these events--a forceful argument for long-term monitoring.

Thus there is great variability at the smaller scales--of the order of 10 days and 10-100 km. Much of the physical energy can be associated with these scales, so much of the biological activity may depend on events of these dimensions.

There is also great temporal variability on the large scales. Based on four years of observations, the north-south pressure difference across the ACC at the Drake Passage can vary from the mean by 25% to 65%. This indicates a commensurate size of fluctuation in the transport of the ACC. Also, we cannot ignore the great seasonal changes in concentration of ice cover and the variations in position of the ice edge. The biological activity of bird and mammal populations at this boundary is particularly important.

It is accepted that the ecosystem in these waters is strongly forced by the physical regime. The general vertical motions, associated with the circumpolar fronts and with dense water formation near the continent, can drive the biological system by supplying nutrients from deep water and by returning the products to greater depths. We now appreciate that these events can vary greatly on relatively short space and time scales and that the local concentrations of organisms may depend on these events. Specifically, we believe that biological sampling conducted without reference to the specific physical regime existing at the time of sampling is unlikely to be as informative as a sampling plan that permits adjustment to concurrent physical observations of the highly variable physical system.

Conclusion: In all stages of planning and execution, the physical and biological components of field studies should be viewed as closely linked joint programs requiring the best efforts of interested scientists. Such joint planning of further Antarctic marine programs should be an essential requirement for all future work. Within the context of studies of the large-scale features, there should be advantages to both disciplines in collaborative studies that clarify mesoscale physics and elucidate the relationship of these features to the biology.

PRIMARY PRODUCTION

A general impression from previous work (El-Sayed, 1970, 1978) is that the basic productivity is not exceptionally high on an annual basis; in fact, it is surprisingly low. Studies of broad areas indicate a range of values for annual production between 16-40 g of carbon/m^2 (Currie, 1964; Holm-Hansen *et al.*, 1977). This is much lower than other commercially productive regions such as upwelling off Peru or on Georges Bank. Thus the dense concentrations of the main herbivore, krill, cannot be attributed directly to generally high rates for production of their food supply. There are not, however, any smaller-scale studies of the relation between herbivore abundance and concentrations of their food.

There is a need to obtain a better understanding of the processes and properties limiting basic production in the Southern Ocean. Why are nutrients apparently never limiting? What is the role of bacterial production in this system? How much of the production is lost by vertical transport? What is the role of meridional transport? Surveys (First International BIOMASS Experiment) carried out in 1981 should indicate some of the answers to these questions. In particular, the use of continuous fluorometric methods, horizontally and vertically, should provide the density of observation to discover possible relations between phytoplankton and the fine structure of the physical environment. Beyond this we should consider the use of sampling methods that can measure physical and biological parameters simultaneously in the horizontal and vertical, possibly using undulating devices. (There is a fuller discussion in Chapter 5.)

A second set of questions concerns the relation between primary production and the herbivores. Are there any locations with high plant biomass--possibly in midwater? Is cell size unusually large, providing suitable food for larger grazers? (Or are the krill able to utilize small cells?) How should we measure production of those types of phytoplankton used by krill, supplementing traditional measures of total primary production? Is there any correlation between krill patches and small horizontal scales of phytoplankton variability? Do krill survive the long winter by feeding on detritus or by going into quasi-hibernation? These questions should guide the design of field programs and call attention to the technical problems of obtaining data on the physical processes, the plants, and the herbivores that are comparable in the appropriate space and time scales.

Conclusion: <u>Measurements relating to phytoplankton abundance and rates of primary production must be closely integrated with the studies of physical variability and zooplankton dynamics. In planning, it should be recognized that different categories of phytoplankton may have different roles in the food web</u>.

HERBIVORES

Although the emphasis is on one species, Euphausia superba, it is necessary to remember that a wide range of other, smaller species plays a significant role in consuming the primary production. Any changes in krill abundance, natural or by harvesting, will probably result in a readjustment of the balance among the phytoplankton and herbivorous species. Thus, in the long term, we require a knowledge of the distribution and biology of these other herbivores and their modes of interaction with E. superba. For this reason, the development of methods to measure herbivore abundance should be aimed toward the estimation of the different size (or species) categories. This problem will be discussed in the chapter on technological developments but should be borne in mind in the following discussion of krill. Data will be needed on the biology of these competing herbivores, and much (or some) of these needed data may be available from past expeditions. For example, the Smithsonian Sorting Center has in its control a collection of approximately 3500 zooplankton xamples and 1100 midwater trawl samples (and also 1900 benthic samples) obtained mainly from Eltanin programs. So far, most of the work on this material has been for systematic and biogeographic interests. Further work on these, and other, samples could advance the scientific goals proposed in this report.

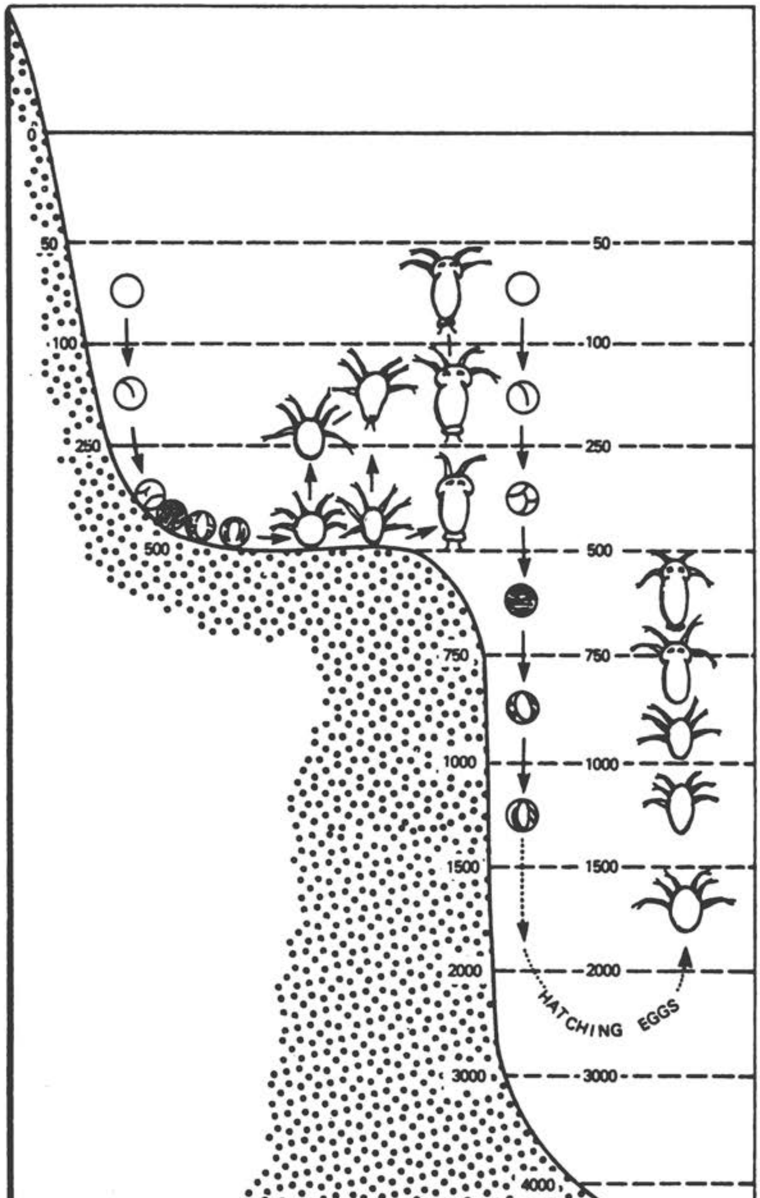
Conclusion: Serious consideration should be given to the use of samples already existing in various collections to supplement field ecological studies.

KRILL BIOLOGY

We do not know the extent of the spawning areas or the spatial cycle of krill during its life span. We assume they breed more than once, but the breeding rates are not known quantitatively. Although these factors might seem to suggest large-scale surveys of krill distribution, which are also of interest to those contemplating exploitation, one must question the probability that these surveys will provide answers to the foregoing questions. It is not possible to follow a particular cohort of krill through one year of its life cycle. Nor is it possible, at present, to determine the age of individuals. One of the peculiarities of krill biology is that the eggs sink several hundreds of meters before hatching and the larval stages then swim back to the surface (Marr, 1962), (Figure 3). This not only emphasizes the importance of physical circulation at all depths (affecting the dispersal of young) but also suggests that the relation between larvae arriving at the surface ready to feed and the locally available supply of food may be especially critical.

An alternative, or complementary, approach is long-term experimental studies. It has proved possible to keep krill in the laboratory for long periods (McWhinnie, 1979), but it appears likely that, at present, they do not behave "naturally" in terms of feeding, growth, and reproduction. Similar problems have been encountered with other crustaceans and overcome with particular species, primarily by improvement in the types of food and containers that can be routinely provided in the laboratory. Thus a longer-range program or experimental study of krill would appear appropriate, with emphasis on ways to achieve better comparison with natural conditions or at least to assess the effects of confinement on the parameters being measured. Although it is unlikely that experiments can duplicate field conditions completely (e.g., hydrostatic pressure), it should be possible to compare freshly caught and laboratory-maintained animals with respect to, for example, "condition factor" and resting metabolic rate. This has been done successfully with other crustaceans.

A second set of questions concerns the behavior of krill in patches and swarms (see next section). The factors influencing this behavior are not known, and there is a need to investigate responses to physical features, food supply, and each other. As part of a more general approach, experimental studies of feeding on natural phytoplankton populations could complement observations on the relationship of krill distribution to phytoplankton distribution. Such studies can be carried out on ships with appropriate space and facilities and have also been attempted at Palmer Station (Antezana, personal communication).



Notes: Readings in m. Hatching in the shallower conditions gives rise to occurrences of nauplii and metanauplii unusually close to the surface.

Source: Marr, 1962.

FIGURE 3 Development of Eggs of *Euphausia superba.*

These experiments could investigate the relationship between the herbivores and their food supply. In regard to swarming behavior, certain clues (Denys, personal communication) indicate that bioluminescence may play a role, and, again, a longer-range program for experimental study of responses to light and other possible factors seems appropriate.

Conclusion: The problems in krill biology invite an emphasis on experimental approaches. Some shorter-period experimental studies of feeding responses and swarming behavior could be conducted on board ships. A longer-term study of growth under different physical and food conditions depends on advances in laboratory rearing and handling techniques, which show promise of duplicating features of the natural cycle of development and reproduction.

KRILL DISTRIBUTION

Studies on metabolism and behavior need to be linked to observations on krill abundance. Most of the evidence on the large-scale features of krill distribution come from the Discovery Investigations, which showed the highest concentrations in an area north of the Weddell Sea (See Figure 2). In all areas, however, but especially in those with high densities, the concentrations are extremely variable, and this variability is the cause of difficulties in the assessment of total stocks and in potential commercial exploitation. Evidence about the smaller-scale krill distributions tends to be circumstantial, relying on visual observations of near-surface concentrations and subsequent deductions of probable scales and densities. BIOMASS Report #10 provides such a "picture" with two types of aggregation: (a) patches (or shoals) with horizontal dimensions of several kilometers and (b) swarms (or schools) with dimensions up to 100 m (although larger swarms have been reported).

Thus, although one can expect krill densities to vary on all horizontal dimensions, the major questions can be grouped into two very different ranges: a large regional scale of the order of 10^2-10^4 km and a local scale of 10^{-1}-10^{1} km. Associated with the former are temporal scales of 1-3 years (krill life-time); the time scales for patches and swarms are not known but are expected to be of the order of days to months. This dichotomy is recognized in the BIOMASS reports as a basis for planning research activities such that general surveys be followed by more detailed studies of patches.

The great variability creates major problems for the assessment of krill densities and sampling of the populations. The documents outlining the procedures for FIBEX (BIOMASS Report Series #13) and other reports raise questions about choice of nets that can sample krill quantitatively. Yet it is accepted that, with an economic use of ship time, net systems, although a necessary component of any sampling program, will not provide the detail essential for assessing the variability on all relevant scales and for establishing relationships to physical and fluorometric measurements. The need to use acoustic methods is emphasized in these reports and is an essential component of surveys on any scale. The descriptions of acoustic estimation methods emphasize the problems of calibrating the acoustic data to obtain absolute measures of abundance and also the difficulties in separating signals from krill and from other organisms. These problems are especially troublesome for the larger-scale surveys, which are aimed at measuring total krill stocks and in which other species are likely to be encountered. For studies of patches and swarms where acoustic methods are indispensable, relative changes can provide valuable data on scales of variability; the swarms tend to be monospecific (and often confined to a single size class).

Different scientific aims require different technical approaches. Acoustic techniques suitable for large-scale stock assessment may differ from those most appropriate for study of smaller-scale patterns. So there is an urgent need for further improvement and application of available acoustic techniques and for the development of newer methods based on detection using several sound frequencies and of side-scan sonar. These needs will be considered in a later section on technological development.

Conclusion: Within the overall effort, research should be directed toward the intermediate and smaller scales of the range of krill distribution.

Commercial harvesting of krill is now at a relatively low rate, approximately 120,000-500,000 tons/year. Yet data on the statistics of this fishery can be valuable, not only in terms of the total resource but also as measures of maximum abundance, since fishing will obviously be concentrated in areas containing swarms. Strong support should be given to schemes for collecting and disseminating as much detailed information as possible on population densities, size structure, and gut contents.

Conclusion: The combination of experimental fishing with research on patches should be encouraged and is an important aspect for international collaboration.

FISH STOCKS

The Antarctic fish stocks may be considered in two groups, demersal and pelagic. The former are the basis of an important commercial fishery by foreign nations; the latter are not yet harvested in any significant quantities.

The Notothenids, which are predominant in the commercial fishery, are essentially benthic feeders, and the fishery is restricted to the relatively small shelf areas. The catch has reached levels of about 260,000 tons/year. Catches have declined recently, which some attribute to overfishing, but there is insufficient information to reach any conclusion on sustainable yields. There is little likelihood that the United States will be involved in this fishery.

On this basis, there is evident need for international regulation and, concomitantly, for improved data, because the catch statistics are inadequate. At present there is no appropriate international organization to deal with these problems. The Convention on the Conservation of

Antarctic Marine Living Resources will form the relevant mechanism, but this convention may not come into force for several years. For this reason, and because several of the harvesting countries are involved, BIOMASS has undertaken activities in this field. Because there is no direct U.S. involvement, and because the ecosystem on which these fish depend is peripheral to the major open ocean pelagic systems, it would not appear necessary to have a U.S. field research program.

Conclusion: General U.S. interest in these fisheries-management problems and the availability of U.S. expertise for resource management indicate that a contribution through NOAA/NMFS would be appropriate.

Pelagic fish provide a quite different set of questions. There is no commercial yield, so the size of these stocks (especially Micromesisties spp.) is not known, but they may be a significant predator on krill. Pelagic fish, together with squid, form the main blanks at the predator level for the overall picture of energy flow in the ecosystem. This lack of knowledge is a limiting factor in estimating the total commercial potential of krill and the effects of such harvesting. Acoustic survey appears the only feasible method unless, or until, a commercial fishery develops.

Conclusion: There is a need to include estimates of pelagic fish stocks in future surveys at both the large and small scales.

SQUID

Squid are an important component of the Antarctic marine ecosystem. Cephalopod beaks are commonly found in sperm whale, elephants seals and Empeor penguin stomachs, and squid are likely to be a major predator on krill and other crustacea. A SCAR/SCOR workshop on squid beak identification will be held. Together with pelagic fish, the lack of any estimates of squid populations creates major problems in assessment of krill dynamics. At present we can do no more than highlight this question.

Conclusion: Information on squid populations will be a valuable addition to our knowledge of the Southern Ocean ecosystems.

SEA BIRDS

It is necessary to recognize that sea birds are marine organisms and can play a significant role as predators. In the Antarctic, it has been estimated that sea birds prey on krill to a level roughly half that of the present populations of whales. This predation is dominated by one species, the Adelie penguin, and calculations of total food requirements have been based on population estimates and biological energy rates.

Improved population counts and more data on energy requirements could improve the estimation of probable total intake of krill, which must still take into account the major gaps in the krill budget related to squid and pelagic fish.

A second set of questions concerns the possibility in certain locations of using changes in bird demography as indices of krill stocks. It is suggested that, since penguins are year-round inhabitants, yearly fluctuations in breeding success should be an indicator of variations in distribution and abundance of certain krill stocks. However, it is not apparent that such demographic data have broad application or can be as easily acquired as certain demographic data on seals or whales. Also, past data from birds are not extensive.

Conclusion: The role of the sea birds should be viewed in relation to local events, and research needs on birds should be considered in the context of a program aimed at the physical and biological dynamics of this part of the system.

SEALS

The four species of true Antarctic seals (Ross, leopard, Weddell, and crabeater) have never been harvested commercially but have provided food for early explorers and currently for dog teams. The southern elephant seal and southern fur seal were reduced to low levels in the late 1800's and early 1900's but the populations are now growing rapidly. Eight nations have ratified a Convention that establishes quotas and provides scientific consultations should these nations decide to take any of these species commercially.

There are demographic data on the decrease of age at maturity in crabeater seals (Laws, 1977). It is assumed that, as with baleen whales, this finding indicates increased availability of their main food, krill. Recent data (Bengston and Siniff, 1981) indicate that the age of maturity may now be increasing; however, because the seals live near the ice edge, they offer a geographically different index of the changes in krill availability from those data provided by most of the whale species. The correspondence of seal and whale demography is an indication of the possibly general nature of the changes in krill stocks. As with whales, availability is possibly a function of local concentration rather than average stock densities. But an increase in krill in the pack ice (where the younger ages of krill may occur) along with a probable increase in their predators, is perhaps the best indicator of a general increase in krill stocks, rather than a local increase of adults in swarms within the areas formerly occupied by larger whale populations.

Conclusion: An understanding of that portion of the ecosystem along the ice edge as well as within the pack ice community appears a necessary complement to more offshore studies. Studies of current and past demographic changes in seals at different geographic locations can indicate the extent of changes in krill populations. Also, studies of competitive interaction among the species sharing the krill in the pack-ice community may prove valuable for future questions relating to nonrenewable resources.

WHALES

There is an international structure, the International Whaling Commission and its various committees, that supervises data collection and analysis and determines management regulations. These data and analyses are the best available indices of the changes that have occurred in the Antarctic ecosystem. They provide essential elements for planning of research and for testing of hypotheses. However, it should be recognized that the needs of the Commission can differ from those of more basic research programs. The needs of the Commission are complementary to research activities, defined primarily in terms of their relevance to major ecological problems; however, answers to these ecological problems are expected to contribute to improved whale-stock management.

The information on changes in baleen whale stocks can be used to estimate total consumption of krill (Beddington, 1980). The large decrease in this consumption has led to the various estimates of the so-called krill surplus. But it is also apparent that this surplus could have been compensated by unknown increases of other predators, for example, seals, birds, squid, and pelagic fish. Thus the only "hard" evidence for an increase in krill comes from the demographic data on decreases in age at maturity and possible increases in fecundity of krill predators. These changes indicate an increase in the rate at which whales consume krill. It has been pointed out, however, that whales can only obtain an adequate rate of food intake by feeding in concentrations of krill well above the large-scale average. Thus the demographic data only relate directly to changes in availability of krill swarms to whales. Inferences about total krill stocks depend on assumptions about the relations between krill in and out of swarms or patches.

Conclusion: The intrinsic scientific interest in krill behavior at smaller scales is relevant to whale management and, especially, to the interactions between whale stocks and the possible exploitation of krill.

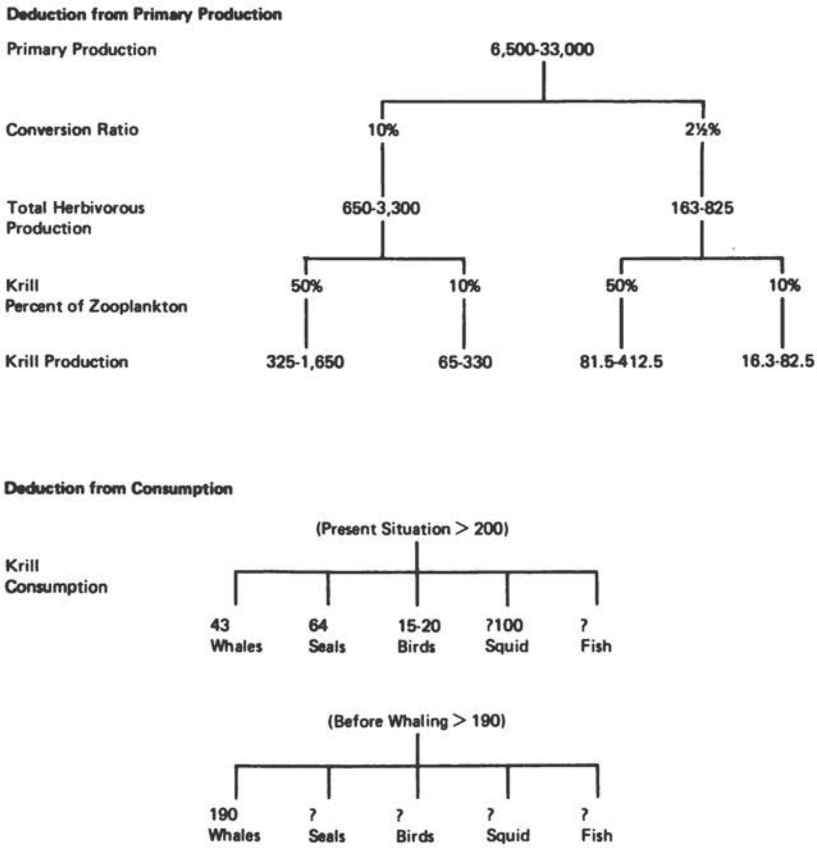
SYNTHESES OF AVAILABLE DATA

Most syntheses have been aimed at producing estimates of total krill biomass and yearly production. The estimates have been made for the present situation and for the conditions before whaling severely depleted this stock of predators. Such estimates can be made either by starting from primary production values and working upward (El-Sayed, 1980) or by working downward from estimates of predator food requirements. In both cases, values are required for biomass and food conversion efficiency of other stocks that compete with krill or prey on them. The available data, and the lacunae, have been summarized by Everson (1977) from which Figure 4 is derived. Such syntheses have been valuable in demonstrating the importance of these gaps in our knowledge.

The arguments about krill harvesting depend on the difference in krill production--and consumption--"before and after" whaling. The estimated difference in whale consumption is of the order of 150 million tons, but how much of this is a "surplus" depends on concomitant changes in populations of the other predators, especially birds, squid and pelagic fish for which there are no data for the two latter groups. Also, the values for krill are longer-term averages, and we do not know the scale or significance of yearly variations.

It has been suggested that a fishery yield of the order of 50 million tons could be available but that this should be approached gradually on a time scale similar to that of whale population increases. The questions are: How shall the effects be monitored? Can the total krill populations be calculated and statistically valid trends determined? Or should we use the demographic changes in the predator populations as indices? The latter approach is attractive because of the interest in the survival and enhancement of the predator populations.

It is possible to produce models of the total system, but the unknown factors, and especially changes in these factors, are likely to preclude their use for management purposes. On the other hand, the demographic data provide estimates of krill availability to whale and seal populations. It has been pointed out that this "availability" is closely linked to the distribution of krill patches and, once again, can focus attention on processes producing these patches as well as factors such as commercial harvesting that may disrupt them.



Note: Figures in millions of metric tons (wet weight).
Source: Everson, 1977.

FIGURE 4 Diagrammatic Methods of Estimating Production of Krill.

Conclusion: Further theoretical, or computer simulation, studies should be directed toward the effects of possible physical and behavioral mechanisms in generating patches and swarms; to the effects of these concentrations on harvesting by whales or ships; and to the consequences of changes in harvesting on rate of intake by these predators.

DIRECTED RESOURCE STUDIES

The studies outlined in the previous sections are intended to combine research toward a better knowledge of the marine ecosystems with emphasis on aspects relevant to resources of the region. It is assumed that, in the long term, the proper evaluation of resources and their effective management must depend on a sound scientific understanding of the underlying structure and functioning of the relevant ecosystems. At the same time, we recognize that the new factors introduced by the Conventions require new commitments to data collection, analysis, and interpretation. The detailed nature of these data sets will be determined by the specific management questions. Many data sets will derive from commercial or exploratory fishing activities by nations participating in the Conventions. It is unlikely that the United States will at present be directly involved in this facet of data collection, but, through the appropriate agencies, the United States should commit effort to the analysis and interpretation of these data.

Conclusion: Resource, conservation, and political needs give rise to targeted research activities. While these activities are selected on the basis of relevance to resource and conservation needs, the research within these targets must be judged initially and reviewed periodically on the basis of scientific quality.

Conclusion: There are also proposals for noncommercial collections of data on unexploited stocks to provide long-term records. Because these long-term needs can require the commitment of funds and effort over many years, their potential value must be assessed carefully. There are two main criteria: (a) Will the data collected provide assessments of ecological parameters with sufficient accuracy that significant changes in these parameters can be detected? (b) Do the parameters reflect changes in the whole or in a major part of the ecosystem at risk?

SUMMARY OF SCIENTIFIC RESEARCH NEEDS

Discussions with the participants, consideration of the relevant literature, and review by the Committee revealed the great range of interesting and important ecological problems in the Southern Ocean. At the same time, our terms of reference required that we make specific recommendations for research. This requirement implies a selection of topics, but we did not consider it possible, or appropriate, to produce a single set of ranked priorities. It is necessary to recognize different methods of approach dependent on the structure of the questions being asked. The Committee believes that topics for research should be considered in three categories: (a) coherent programs involving several investigators and several years of support, (b) special science projects directed to certain critical questions, and (c) individual research. On the basis of our discussions, we see a continuing requirement to maintain and encourage individual initiatives through the usual system of peer review of unsolicited proposals. There is also, however, a need to ensure that scientific aspects of importance to general questions of resource conservation be suitably addressed. These needs can be met through the development of a few coherent longer-term programs and by highlighting certain topics that need attention within the overall ecological framework. The three categories are intended to provide support across this range of activities. Certain priorities for each category are outlined here.

Coherent Projects

1. The physical, chemical, and behavioral processes underlying the formation and persistence of krill aggregations should be studied because of their great ecological interest. An understanding of these processes is essential for management of any krill

harvest and to assure maintenance and improvement in whale stocks. This work should build upon the strength of the U.S. program in Antarctic physical oceanography (see Appendix E.2).

2. Processes in and near the ice pack during seasonal formation and retreat of the ice edge should be studied. This is a special environment whose seasonal variations extend across a major part of the Southern Ocean (Figure 5). Because of its great extent it is important to many species of birds and mammals and to components of krill life history that could be of great significance for their overall life cycle. Further, this ecosystem could be most seriously affected by proposals for development of nonrenewable resources (see Appendix E.1).

The Committee sponsored workshops to begin consideration of the recommended research programs. Reports of these workshops are Appendixes E.1 and E.2, respectively.

Special Projects

Certain gaps in our knowledge of the Antarctic ecosystems that limit our overall assessment of krill dynamics would be aided by appropriate experimental studies. More studies should be made on the populations and feeding biology of squid and pelagic fish because of their critical roles as predators. Innovative research on these questions and the development of the necessary techniques should be encouraged.

Individual Research

Favorable consideration should be given to any proposal containing new ideas for research on Antarctic marine ecosystems. New investigators, especially, should be encouraged to propose and pursue research on these ecosystems.

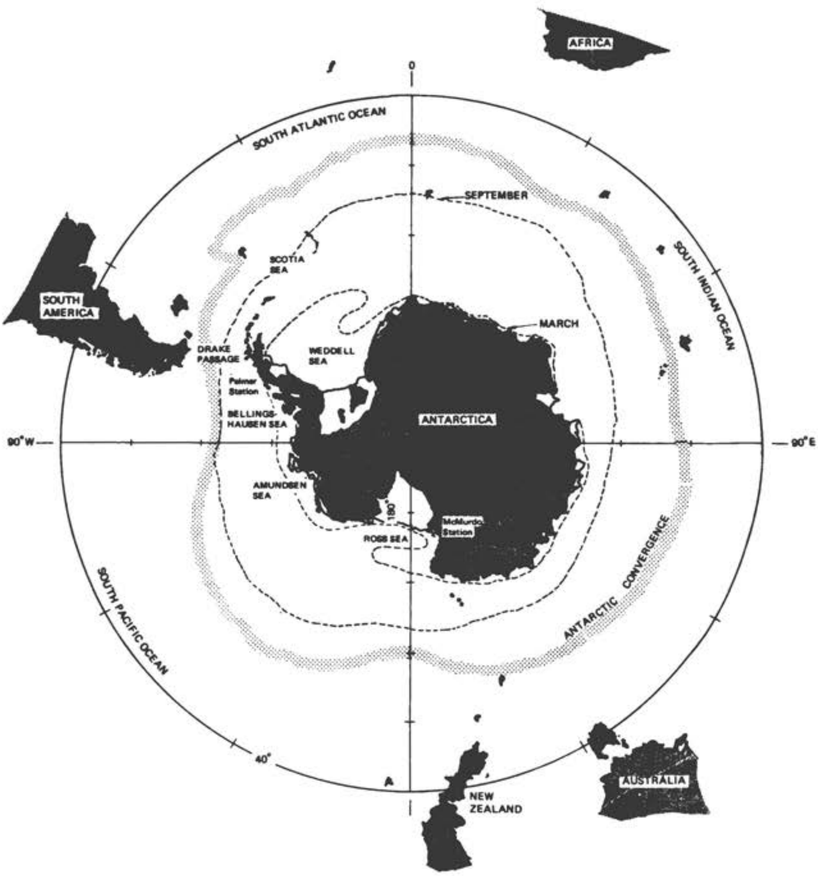


FIGURE 5 The Southern Ocean, Showing the Position of the Antarctic Convergence and Variations in the Boundary of the Pack Ice.

5
Technical Developments

In the discussions of the components of the Antarctic marine ecosystems, it became apparent that, for many features, the limiting factors involved methodology. Data will be required at greater rates than now available, in locations not accessible to ships, or in forms not possible with present instrumentation.

These problems are not peculiar to the Antarctic, and they form one of the possible links between research here and in other ocean regions. The costs, and difficulties, of Antarctic research, however, impose special reasons for proposing that developments in such technology be applicable to studies in the Southern Ocean.

SATELLITES

The general predominance of cloud cover in the Antarctic indicates that only infrequently (10-30 percent of the time) can the sea surface be observed, and then only a small fraction of the relevant area. For this reason, measurements requiring direct visual observation, such as sea-surface temperature or ocean color, have a limited use and cannot be regarded as a regular component of a sampling program. However, the information that may be obtained at scales of 1-100 km can reveal structural features of the physics (temperature) and comparisons with the biology (color).

Conclusion: Satellite data, gathered on a few occasions when relevant surface samples are available, could be valuable indicators of possible links between physical and biological processes.

The major use of satellites in the Antarctic has been to provide communication with several hundred drifting buoys deployed for meteorological studies. There is an obvious extension to physical oceanographic studies and a potential for biological measurements from these buoys, especially for following changes in color and number of organisms occurring over time within a particular body of water. The costs of each buoy would be greater than for meteorological purposes, but these costs should be compared with those of other methods of data collection.

Conclusion: Drifting buoys can be a valuable component of integrated physical and biological sampling programs.

The ice edge is defined as a hydrographic and ecological system rather than a geographical location. The exact nature of its movements and form are essential information for both physical and biological studies.

Conclusion: Satellites data on changes in ice limits provide a major source of information that will be valuable to more detailed studies at the ice edge.

UNATTENDED BIOLOGICAL INSTRUMENTATION

It seems probable that relevant biological data can be obtained from unattended instruments, especially (a) drifting buoys and (b) moored arrays. At present (Whitledge, submitted for publication), existing fluorometers can be used in moored buoys to collect data on phytoplankton over periods of several weeks. Development of special fluorometers with lower power requirements should be possible and could extend the sampling time as well as decrease the battery requirements. Acoustic profiling from moored arrays or drifting buoys is feasible if methods of data processing and storage can be devised. Other measurements, such as intensity or frequency of bioluminescence, are possible, but there would be a need to determine how such measurements can be related to plant or animal population densities. In physical oceanography, moored and drifting instruments have led to major advances not merely in data collection but in the basic concepts of the science.

Conclusion: Drifting and moored instruments should be developed for use in biological oceanography, and the Antarctic should be considerd as one area where their deployment would be most valuable.

ACOUSTIC METHODS

It is accepted that acoustic methods, based on frequencies around 120 kHz, are essential for the study of krill populations. At present, the questions focus on the ability to assess these populations in terms of some biological unit such as total number, biomass, or density per unit surface area. There are three factors: (a) calibration of instruments, (b) estimation of target strength in biomass units, and (c) nonrandom distribution of organisms. Calibration is possible at present with errors between ships of less than ±50 percent, but even calibration of this low accuracy is often not attempted or achieved. Estimation of target strength in biomass units has not been made, and the likely errors are not known. The estimation of nonrandom distributions depends on survey design, and definition of probable errors must be regarded as one aim of the field work.

Estimates of total krill stocks have ranged from 180 million to 1400 million tons with the most likely values in the range 200 million to 600 million tons. Given the present sources of error, it is not clear that acoustical estimates can improve the second set of limits significantly, although this should be possible with effective calibration and target strength estimates and with knowledge of the statistical distribution of patches and swarms. For management purposes, however, information on the effects of removal of, say, 5 million to 10 million tons is needed. Given the probable yearly variability, one could expect such changes to be below the resolution of general survey methods. Again, the survey problems and the management questions focus attention on the need to study the processes for patch and swarm formation where a variety of acoustic techniques are essential and available.

The data in Figure 4 reveal the need to know something about the smaller herbivores as well as the krill. These organisms can be detected using higher frequencies. The separation of different size groups requires the simultaneous use of several frequencies. Such techniques are being developed for use in other areas.

Conclusion: Developments in acoustic techniques should include the Antarctic as one of the major areas for application because the interrelationship of different species within and outside the krill swarms is an important ecological and conservation problem.

TOWED SAMPLERS

We have stressed the need for comparable physical and biological data, especially in relation to acoustic data. Work in other areas has shown that many, but not all, of the variations in acoustic signals can be related to physical structure. To separate the "physical" from the "biological" responses requires data on density structure and on phytoplankton concentrations. Again, methods for these forms of sampling have been developed and are being further refined. We expect to see instrumented "packages" that can identify the relevant features of the physical processes, the phytoplankton, and the herbivores to depths of 100 m and at horizontal scales of less than 1 km. Such sampling systems will be essential for the Antarctic work.

Conclusion: Support of developments using towed bodies for simultaneous physical and biological measurements is needed to ensure that their design will be appropriate for Antarctic research.

SUMMARY

Ecological research in the Southern Ocean is severely limited by the technical capability of describing the systems and relating them to their physical and chemical environment. No single requirement, for ships, acoustic detection, moored instruments, or remote sensing, is predominant. Developments in all of these methodologies are needed.

Conclusion: Developments in technology not only form part of a general advance required by biological oceanography but have special relevance to the Antarctic; future equipment design and construction should include their use in this region as a specific and special aim.

6
Ships

The most important facility for research is, necessarily, suitable vessels. In general, it is essential that the United States have the ability to pursue a wide range of activities involving both open ocean studies and work in or near the ice pack.

Long-term planning should include the design and construction of the kind of vessel that will permit a wide range of research activities. Because we foresee a continued interest in and use for such research, these plans should not be restricted by the lack of capabilities that other nations will certainly have. At the same time, these requirements must be viewed in the context of the general needs of the oceanographic community. The Ocean Sciences Board of the National Research Council is conducting a study of long-term vessel requirements, and the special needs of the polar community must be included.

There appear to be two immediate short-term options: (a) refurbishing the Eltanin to extend its useful life by 10-15 years and (b) provision of a smaller ice-strengthened vessel specifically for work in the ice to be combined with the use of long-range oceanographic ships for open-water work.

(a) A major refitting of the Eltanin is under consideration. However, the lower costs of such a refitting, compared with those of new construction, will be offset by the high yearly costs of operation and maintenance. Data provided by the NSF Polar

Programs Division indicate that, after a 10-year period, total costs for the Eltanin could exceed those for a new vessel.

(b) There exists within the present academic fleet some capacity to carry out research in the Antarctic. But it is clear that, even for the specific programs proposed here, such vessels are not the complete solution. It is possible, however, that particular programs of work to study the special ecosystems existing near and in the ice pack could be undertaken from a smaller (150-170 ft) ice-strengthened vessel of the type used by the Norwegians. As an interim measure, consideration should be given to the use of such vessels for specific programs on a 2-5-year time scale. In general, the lack of adequate ships is seen by many as the major factor inhibiting increased interest in biological research in this region.

Conclusion: U.S. plans must provide for construction of an ice-strengthened Antarctic research vessel.

7
National and International Management

The Antarctic Treaty established a politically unique framework for control of the region consistent with the concept of peaceful use. Scientific study, carried out through international collaboration, was intended to be the primary activity of the participating nations, following the pattern established in the International Geophysical Year.

In this context, it is appropriate that in 1975 the NSF was made the lead agency in the United States for research and budgeting. Overall guidance is provided by the Antarctic Policy Group (consisting of the Department of Defense, the Department of State, the NSF, and, when appropriate, other interested agencies).

The United States was a prime mover in establishing the Antarctic Treaty, thus preservation of the aims of this Treaty is a prime U.S. objective. In recent years, however, major questions have arisen relating to exploitation of renewable and nonrenewable resources--key issues not covered in the original Treaty. The United States has taken a leading role in setting up the new Convention on the Conservation of Antarctic Marine Living Resources so that an appropriate structure for the management of living resources shall be in place even though the U.S. may not participate in harvesting. The United States is concerned that similar measures be available in connection with nonrenewable resources.

These developments introduce vital new elements into the national and international management of research (and of funding) for the marine ecosystems in the Antarctic. The major requirement for the NSF has been to maintain a constant level of effort and a balance among disciplines in the scientific programs. The new issues raise questions about the nature of research needs and the criteria not only for appraising proposals but also for selecting new methods of research coordination in relation to the new issues and to other agencies. These aspects form the basis on which the United States developed the following general policy goals (U.S. Congressional Hearings, May 1, 3, 1979):

"1. To maintain the Antarctic Treaty and insure that this continent will continue to be used for peaceful purposes only and shall not become an area or object of international discord."

"2. To foster cooperative scientific research for the solution of worldwide and regional problems including environmental monitoring and prediction and assessment of resource potential."

"3. To protect the Arctic environment and to develop appropriate measures to insure equitable and wise use of living and nonliving resources."

"4. To promote the free exchange of information."

"5. To maintain a suitable presence in Antarctica which continues to provide leadership in the development of the area, and which preserves U.S. rights and protects future national interests in Antarctica."

The NSF role as lead agency must be placed in the context of these goals. The Foundation is expected to take some initiatives in defining research relevant to resource and conservation questions in addition to its support of basic science. The present NSF system, typified by unsolicited proposals from individual investigators, will probably not be adequate for the resource questions. The IDOE (International Decade of Ocean Exploration) approach with defined categories of issues to be funded through group projects can be an effective way to identify important research questions within the broader context of resource issues. We have used this approach in defining problems to be addressed in "coherent programs."

At the international level, the BIOMASS program has recognized the same questions of resource management needs and has produced broad plans that include projects intended to provide information relevant to these aspects as well as to study less mission-oriented scientific questions.

We wish to avoid a dichotomy between basic and directed research, but we realize that an exact balance in interests between basic science and resource-oriented studies is not practical or possible. In the long term, the proper evaluation of concerns with resource development must depend on a sound scientific understanding of the basic structure and functioning of the relevant ecosystems. There is and should be a broad overlap in studies aimed at these two main objectives, but, necessarily and properly, there are different priorities among U.S. agencies and among different countries participating in the BIOMASS program. In this report we propose that the criteria for selection of research topics be: (a) quality of science and (b) relevance to resources and conservation aspects.

Conclusion: Based on the existing management objectives of the National Science Foundation, the quality of science must have priority in defining the research objectives for field programs supported by the Foundation in the Antarctic.

We also recognize that, for the directed research required by agencies with missions related to resource development and conservation, priority must be given to the acquisition of information required to meet their objectives. Within this context, programs should be judged in terms of scientific quality. On this basis, decisions about the amount of effort and funds to be devoted, for example, to acquisition and analysis of data on demersal fish or sea bird populations may depend primarily on the concerns within relevant agencies for the exploitation or conservation of these populations. Given such concerns, however, it is necessary to consider whether existing or proposed survey data will provide an adequate basis for management, what other information is needed, and whether international collaboration is appropriate.

It is apparent that the increasing potential for exploitation of nonrenewable as well as renewable resources will require considerable expansion in the efforts devoted to the evaluation of possible consequences. The Conventions in place, or proposed, will generate many questions requiring significant support for their elucidation. Although we regard the field research proposed here as major long-term contributions, we realize that separate, and substantial, inputs will be needed from groups concerned with the specific resource issues. We would recommend that such groups have a major role in the determination and funding of the necessary targeted research.

Conclusion: In terms of national management, specific program aims should be defined initially in the context of separate priorities for marine ecological research, for resource management, and for conservation. The nature of these different priorities and the level of support made available are matters for the individual agencies in relation to the total U.S. commitment to studies in the Antarctic.

Conclusion: Implementation of aims, through field programs, data analysis, and evaluation, will demand integration of efforts at sea and in the laboratory among scientists from many organizations, academic and federal. It is essential that, as these different aims are realized in specific projects, the planning and execution be carried out with the closest collaboration among the various organizations. This cooperation is especially desirable because the great cost of logistics of field operation demands the utmost efficiency.

At the international level there are, correspondingly, a diverse set of organizations with interests in Antarctic marine studies. Four of these are involved in the international field program BIOMASS--each with special interests: SCAR in the Antarctic, SCOR in oceanography, IABO in biological oceanography, and ACMRR in resource management. The recent survey--FIBEX--involving 10 countries and 17 ships should provide some insight into the structure and function of the Antarctic marine ecosystem.

Conclusion: BIOMASS has strong support in several countries with major Antarctic interests, and the United States should continue to develop an Antarctic marine biological research program within this framework. We have indicated that the U.S. should develop its own role within this structure. General approval of the aims of BIOMASS is not inconsistent with special directions for United States studies. The United States should join in providing financial support through SCAR for an international BIOMASS secretariat; however, the secretariat should be relatively small and attached to a program of Antarctic studies.

STEERING COMMITTEE FOR ANTARCTIC MARINE ECOSYSTEM RESEARCH (AMER)

BIOMASS is only one of the international activities with which the United States is concerned in the Antarctic. Others include the IWC, the Seal Convention, and the Southern Ocean Coordination Group of the Intergovernmental Oceanographic Commission. Of special importance is the Convention on the Conservation of Antarctic Marine Living Resources. Any steering committee required for BIOMASS only may be too narrow. Some continuing oversight of international activities and their relationship to national programs seems necessary.

Conclusion: To meet the needs for national and international coordination of AMER, including those of BIOMASS, a continuing committee will be required consisting of scientists representative of the physical, biological, and technological programs in being or envisaged in academic and federal institutions.

- General committee functions should include:

1. Providing counsel for the U.S. Antarctic marine ecosystem research program;

2. Providing advice to U.S. agencies and commissions.

o Specific functions should include:

1. Serving as the U.S. BIOMASS committee;

2. Coordinating AMER planning workshops.

8
Funding

The recent funding for Antarctic marine science research is given in Appendix A and demonstrates the role of marine ecosystems studies in the overall budget. Funding for science, excluding ships and shore facilities during 1981, is about $3 million.

This report has stressed the general significance of marine ecosystem studies in the Antarctic in the context of biological oceanography as a whole. We have also emphasized the rapidly increasing importance of resource-related research, and we recognize that this research will undoubtedly need increased support from non-NSF sources.

The major fiscal feature of Antarctic research is the large proportion of the total budget devoted to logistics. The location and nature of the environment make this factor understandable, and it is a necessary element in our presence in this region. However, the large logistics/science ratio implies that in conditions of relatively constant funding, inflationary increases in logistic costs can result in drastic and unexpected reductions in science support. We recommend that some "protection" be afforded to the science component of the budget.

Our specific conclusions regarding field programs will require support at a level markedly above the present rate of funding. Detailed evaluation of costs will require program definition and development by working groups. However, comparable coherent projects involving multidisciplinary activities, such as Warm Core Rings, Coastal Upwelling Ecosystem Analysis or Processes and Resources of the Bering Sea Shelf (PROBES), have yearly costs, excluding ship time, in the range of $1.5 million to $3.0 million.

Conclusion: <u>The expected cost of the coherent programs outlined here will be in the range of $3 million to $6 million per year, excluding ship support. This amount should be in addition to the present level of scientific effort, approximately $3 million per year. The total research cost, excluding ship support, would be $6 million to $9 million.</u>

9
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Appendix A:
Support for Antarctic Marine Sciences (Number of Projects and Amount in Dollars)

	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980
Division of Polar Programs						
Marine bacterial studies	- -	- -	- -	2 $ 63,800	1 $ 85,531	1 $ 73,783
Primary productivity studies	1 $ 4,600	1 $ 60,000	3 $173,700	3 $168,457	4 $124,352	3 $502,578
Zooplankton studies	2 60,200	- -	1 $ 56,000	3 $135,128	3 $129,999	3 $ 70,894
Benthic studies	2 $ 99,000	2 $127,900	1 $ 50,000	2 $ 63,800	- -	2 $163,441
Vertebrate studies						
Birds	7 $121,123	5 $121,500	4 $118,200	3 $107,976	5 $141,099	4 $173,895
Fish	2 86,400	- -	1 $ 63,600	- -	- -	- -
Seals	2 $113,500	3 $162,100	3 $172,700	2 $153,139	4 $201,967	3 $191,510
Whales	- -	- -	- -	1 $ 30,600	1 $ 38,413	1 $ 33,848
Organic chemistry studies	1 $ 21,200	1 $ 36,900	- -	1 $ 39,500	- -	1 $ 36,807
Physical oceanographic studies	4 $209,200	5 $ 531,700	5 $ 517,800	2 $ 230,144	4 $ 224,359	3 $ 261,360
Sea-ice studies	- -	1 43,300	- -	1 $ 150,200	1 $ 129,527	1 $ 129,902
Smithsonian Sorting Center	3 $137,100	- -	2 $ 64,000	2 $ 75,558	2 $ 212,087	1 $ 101,139
Design plan for ice-strengthened research vessel	-	-	$ 26,300	$ 201,662	-	-
Subtotal for DPP	$852,323	$1,083,400	$1,242,300	$1,419,964	$1,287,334	$1,739,157

	FY 1975	FY 1976	FY 1977	FY 1978	FY 1979	FY 1980
International Decade of Ocean Exploration						
International Southern Ocean Studies (ISOS)	11 $901,800	16 $1,189,500	16 $1,248,600	13 $1,591,800	13 $1,259,383	13 $1,600,000
Other physical oceanography	-	-	-	3 $ 83,700	-	-
Total projects	35	33	37	39	38	36
Total expenditures for research	$1,754,123	$2,272,900	$2,490,900	$3,095,464	$2,546,717	$3,339,157
Direct science support	$2,864,866	$3,787,697	$4,482,800	$4,900,000	$7,500,000	$7,070,000
Total for NSF	$4,618,989	$6,060,597	$6,973,700	$7,995,464	$10,046,717	$10,409,157
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION						
Treaty negotiations				$ 50,000	$ 50,000	$ 50,000
Data analysis				50,000	50,000	50,000
Science planning and participation in FIBEX						100,000
Total for NOAA				$100,000	$100,000	$200,000
MARINE MAMMAL COMMISSION (Number of Projects and Amounts in Dollars)						
Data analysis and science planning	1 $ 16,333	3 $ 43,445	2 $ 9,628	- $ -	1 $ 10,000	
Total U.S. Government Support for Antarctic Marine Sciences	$4,618,989	$6,076,930	$7,017,145	$8,104,092	$10,156,717	$10,619,157

Appendix B:
National Organizations and Committees Concerned with Antarctic Marine Ecosystem Research

I. U.S. Government

1. National Science Foundation

   o Division of Polar Programs
   o Division of Ocean Sciences

2. National Oceanic and Atmospheric Administration

   o National Marine Fisheries Service
   o Research and Development

3. Marine Mammal Commission

4. Department of State

   o Office of Oceans and Polar Affairs

5. Antarctic Policy Group

6. National Security Council

7. Department of Energy

8. Department of Defense

9. Department of the Interior

10. Environmental Protection Agency

11. Council on Environmental Quality

12. National Aeronautics and Space Administration

II. <u>Nongovernmental Groups</u>

1. National Academy of Sciences/National Academy of Engineering/Institute of Medicine/National Research Council

   o Polar Research Board
   o Ocean Sciences Board

2. Center for Law and Social Policy

3. Monitor (consortium of over 30 environmental groups)

Appendix C:
International Bodies Concerned with Antarctic Marine Ecosystem Research

I. Intergovernmental

1. Antarctic Treaty Nations (Argentina, Australia, Belgium, Chile, France, Federal Republic of Germany, Japan, New Zealand, Norway, Poland, South Africa, Soviet Union, United Kingdom, United States)

2. Convention on the Conservation of Antarctic Marine Living Resources

3. Convention for the Conservation of Antarctic Seals

4. Food and Agricultural Organization of the United Nations

   o Advisory Committee on Marine Resources Research

5. Intergovernmental Oceanographic Commission

   o Programme Group for the Southern Oceans

6. International Whaling Commission

II. Nongovernmental Organizations

1. International Council of Scientific Unions

   - Scientific Committee Antarctic Research

   - Scientific Committee Oceanic Research

   - SCAR Group of Specialists on the Southern Ocean Ecosystems and Their Living Resources in cosponsorship with SCOR, International Association of Biological Oceanography (IABO) and Advisory Committee on Marine Resources Research of FAO (ACMRR)

2. Antarctic Southern Ocean Coalition (ASOC)

3. Sierra Club International

4. International Institute for Environment and Development

5. International Union for the Conservation of Nature and Natural Resources (IUCN)

Appendix D:
Antarctic Ship Facilities

ICE-STRENGTHENED RESEARCH VESSELS

There are a limited number of ships in the U.S. inventory that are capable of and practical for operating as mobile platforms for polar oceanographic operations. The U.S. Coast Guard controls and operates the U.S. icebreakers, consisting of two polar-class and three smaller vessels that can operate in pack ice; however, their ability to support science is extremely limited, and other missions have priority in their operations.

The U.S. R/V Hero, a 125-foot trawler-research vessel operated by NSF in waters surrounding the Antarctic Peninsula, recently completed a thorough overhaul in the United States. She is incapable of deep-sea research or work in heavy pack ice.

Only two U.S. Navy-controlled ships are adequately ice-strengthened and suitable for polar oceanographic operations: The USNS's Mizar and Eltanin, which were built and launched in 1957 as ice-strenghthened cargo ships in the 250-foot class. Mizar and Eltanin were both reconfigured, in 1964 and 1962, respectively, to ice-strengthened oceanographic research configurations. Mizar is operated by the MSC under the technical control of the Naval Electronics Systems Command in dedicated, specialized research for the Navy.

The NSF operated the USNS Eltanin from 1962 to 1974 in the Southern Ocean. From 1974 to 1979 the ship, renamed the Islas Orcadas, was operated on a joint basis between the U.S. and Argentina, and in 1979 she was returned to the United States Navy. The Eltanin/Islas Orcadas research program provided the cornerstone for the U.S. research program in the Southern Ocean. The ship was recently surveyed and found to be sound; however, approximately $9 million is required to refurbish the ship.

In a letter of January 1980 to U.S. Government officials, Philip Handler, the President of the National Academy of Sciences, expressed the joint concern of the Polar Research Board and Ocean Sciences Board on the declining opportunities available for U.S. scientists to conduct important research in ice-covered seas.

The Boards recommended:

1. To meet research needs in Antarctic waters, the USNS Eltanin should be modernized or, depending on cost-benefit studies, an ice-worthy replacement ship should be provided as soon as possible.

2. Pending modernization of the USNS Eltanin or acquisition of an ice-worthy replacement ship, use should be made of suitable chartered ships and oceanographic vessels of the UNOLS fleet for both Arctic and Antarctic research, and funds should be made available for this participation by the agencies concerned.

RESEARCH VESSELS OPERATING IN THE U.S. ANTARCTIC PROGRAM

1980-1981

R/V Melville
R/V Hero

1979-1980

ARA Islas Orcadas (Argentina)
R/V Hero
R/V Atlantis II

1978-1979

ARA Islas Orcadas (Argentina)
R/V Melville
R/V Hero
R/V Knorr

FOREIGN VESSELS INVOLVED IN ANTARCTIC MARINE ECOSYSTEM RESEARCH 1980-1981

Argentina
Eduardo L. Holmberg

Australia
Nella Dan

Chile
Itsumi

Federal Republic of Germany
Polarqueen
R/V Meteor
Walther Herwig

France
Marion-Dufresne

Japan
Fuji
Umitaka Maru
Kaiyo Maru

Poland
R/V Prof. Siedlecki

S. Africa
S.A. Agulhas

Soviet Union
Odyssee
Academic Knipovich

United Kingdom
RRS John Biscoe

Appendix E. 1:
Research Goals for the Southern Ocean Ice-Edge Zone

Report of a Workshop Held at
Woods Hole Oceanographic Institution

April 13-14, 1981

PARTICIPANTS

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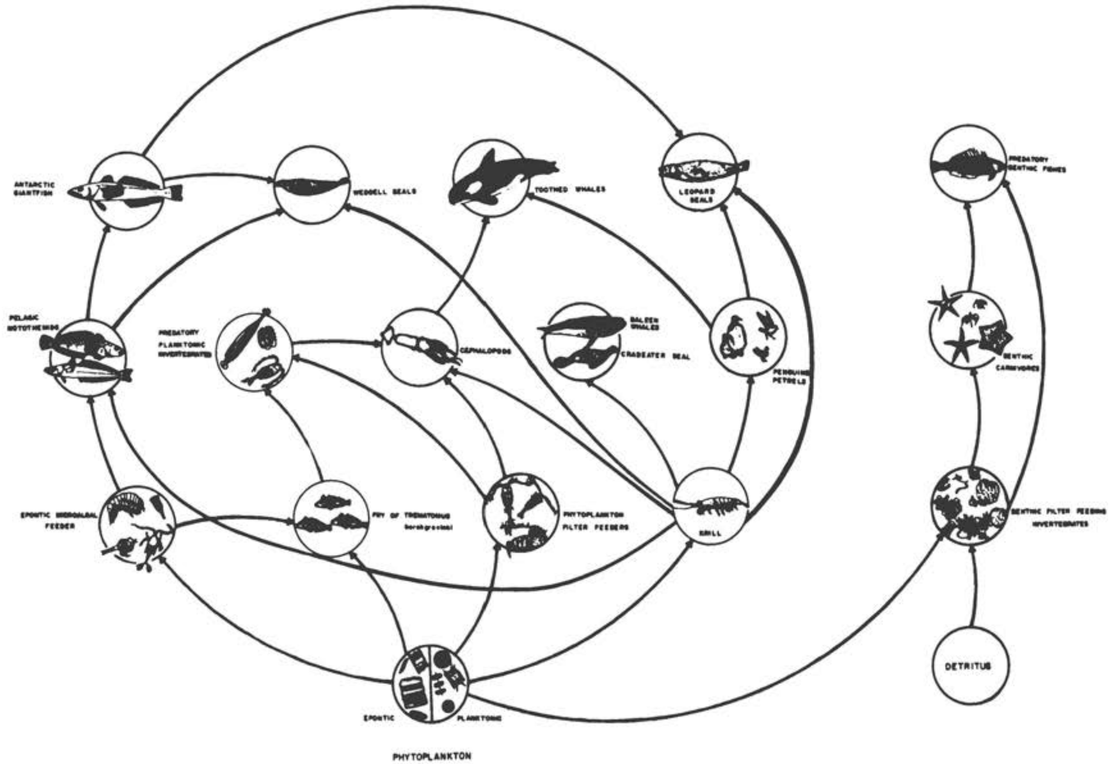

Food Chain Relationships in the Pack Ice Zone (After El-Sayed, 1970).

INTRODUCTION

The Ice-Edge Ecosystem

The Antarctic pack-ice region has long been recognized for its dynamic nature and the seasonal advance and retreat of its ice-edge zone. The physical and biological changes that occur annually are dramatic. Southern Ocean sea ice is mostly seasonal (Mackintosh, 1972), and only in a few areas such as the western Weddell Sea does it survive the summer. The waxing and waning of the ice cover from a 2×10^6 to 4×10^6 km^2 February minimum to 18×10^6 to 20×10^6 km^2 maximum in September produces a rapidly moving ice edge. A seasonal migration rate of 3 to 5 cm/sec is required for most sectors of the Southern Ocean, but higher migration rates occur in the South Atlantic. In addition to seasonal variability are the dynamics induced by synoptic weather systems. Satellite observations in the 1970's suggest that the nonseasonal variations result in significant anomalies from mean seasonality (Zwally *et al.*, 1979).

The nature of the ice edge varies greatly. Often it is a sharply delineated boundary between complete ice cover to open water within a scale of a kilometer or less. At other times loose pack separates significant concentrations of ice from open ocean over distances of many tens of kilometers (Gordon, 1972). Variations from a well-defined to a diffuse ice edge seem to be associated with wind direction, and the transition time from one state to another can be on the order of a day. The major factors responsible for ice-edge position and characteristics are freezing, melting, and advection. The balance of these determines the extent of advance or retreat, as well as the sharpness of the ice edge.

Associated with the pack is a unique flora and fauna, including certain species of algae, crustaceans, fish, mammals and birds. Such an association has been known qualitatively for some time (e.g., Marr, 1962), but quantitative correlations are few, perhaps owing to the difficulty in working in the ice by ship.

Particularly important to pack-ice organisms must be the extensive rapid seasonal fluctuations in the extent of the ice. In fact, the retreating ice edge may be critical to certain life history patterns in these organisms. As polynyas and leads form along the continental margin and the winter pack recedes, open areas will be exposed to sunlight, thus reviving algae from dormancy. Zooplankton could concentrate near resulting blooms, some of which may be seeded by algae in the disintegrating ice (Ackley et al., 1979). Dense concentrations of young krill have frequently been encountered at the large-scale interface between the pack and open seas, particularly in winter and spring (Marr, 1962); baleen whales used to follow the retreating pack edge in their intensive feeding activity (Mackintosh, 1974); and bird numbers and species diversity are known to reach their seasonal maximum in certain areas during weeks when the ice edge retreats most rapidly (Ainley et al., 1978).

Organisms that live within the Antarctic marine ecosystem have adapted to the dynamic movement of ice in ways that are mostly unknown and with dependencies on the physical processes that are virtually unexplored. The main report recommends that studies of processes in and near the ice pack during the seasonal formation and retreat be a major focus for an integrated multidisciplinary research project. This Appendix outlines a research plan for such studies. This plan takes the general view that any understanding of the biological processes of organisms in this area will come about only through the integration of biological life-history measurements with data and models of the dynamic physical processes at the ice edge.

These observations indicate a need for increasing our understanding of ice-edge phenomena, particularly of the dynamic interaction between the ice and its associated biota. To achieve this understanding, the following major objective and specific questions are advanced:

General Objective

To determine the biological and physical characteristics of the ice-edge ecosystem, including their spatial and temporal scales.

Specific Questions

1. What are the associations between organisms and the seasonal ice; how does the ice mass balance affect these associations, species interactions, life histories, and ecosystem processes?

2. How does vertical and horizontal mixing of waters associated with melting and freezing enhance the biological productivity at the ice edge?

3. How do ecological processes, community composition, and abundance of organisms change in time and space at distance from the ice edge?

4. How does the horizontal and vertical circulation of the ocean interact with the pack ice?

5. What is the nature of ice dynamics and movements near the edge; and how do these dynamics affect the edge disintegration, oceanic circulation, and biological processes?

6. What are the relative roles of surface ablation versus oceanic warming in the ice-edge disintegration?

ICE-EDGE BIOLOGY

Primary Production

Biological interaction with sea ice is particularly notable at the primary production level. The sea ice influences and is influenced by physical processes, thus the coupling between physical properties of the seawater, the sea ice, and the phytoplankton population may be complex. However, a few generalizations, based on published data seem appropriate:

1. Sea ice forms an environment that allows the growth of an algal community, dominated by diatoms, in the layers adjacent to and in contact with seawater. Algae may also occur within the ice, and some forms grow on the ice surface. The algal community on the undersurface of the ice may serve as an important, concentrated food source for higher trophic levels early in the season. The cells are maintained in good light intensity under the ice and do not mix into the water column. Furthermore, this community can seed the open waters at the ice edge. Important questions concerning these ice algae include the sources of nutrients, the light climate, and their availability as food to higher trophic levels.

2. As the ice breaks up, a bloom develops in the water. This has been documented in Antarctic waters but never examined in detail. The relationship of the bloom to local hydrographic conditions, the species composition as the bloom forms, and successional relationships as the ice retreats are subjects for study. Local conditions such as water column vertical and horizontal structure, effects of diluted ice-melt water, possible upwelling and other water movements all may play a major role.

Organic Matter Transfer

Plant populations growing in and on the undersurface of the sea ice and in the photic zone of the water column provide the carbon and nitrogen sources for animals living in association with the ice zone. The initial transfer of organic matter through the remainder of the food web depends not only on the relative numbers of grazers present but also on the composition of the plant population and size of the individual cells. Cool, nutrient-rich waters tend to host diatom assembleges, which may be composed of large (10-100 um) individuals or long chains of considerable size. Under these conditions, the trophic exchanges to zooplankton/micronekton and then to the squid, fishes, birds, and mammals are few in number, but the transfer process is highly efficient. It is thought that the Antarctic system is of this kind with krill (Euphausia superba and other euphausiids) acting as the key ecological species standing between primary producers and higher trophic levels.

It is not known for the Antarctic shelf region what proportion of the organic matter synthesized in the water column is taken by krill and other grazers (copepods, amphipods, larvaceans, and others) and whether the coupling is generally tight (i.e., most incorporated in pelagic food webs) or if portion of the bloom sinks to feed seabed populations, as occurs in the southeast Bering Sea. This partitioning of the food source must be examined in the seasonal context of community succession (both phytoplankton and zooplankton/micronekton) as the ice-edge retreats and in relation to the oceanic and shelf-water masses. In particular, the food dependencies of the developing krill should be addressed. It may be assumed, as a first approximation, that the early life-history stages probably use a different portion of the plant/animal community than do the larger juveniles and adults. If the krill function like the anchovetta (Peruvian anchovy), they will be dependent on the microzooplankton community for food (copepod eggs, nauplii, copepodids) in larval and postlarval stages, but later the developing juveniles and adults would switch to both plants and animals as forage species. This and other parts of the program relate closely to the second project on the dynamics and patchiness of krill populations.

Food Web Kinetics and Animal Life History Patterns

The influence of ice-edge dynamics on the many vertebrate and invertebrate species is virtually unknown. Observations of changes in vertebrate animal species abundance and patterns along the ice edge zone have been made (Ainley and Jacobs, 1981; Cline et al., 1969; Erickson et al., 1971; MacKintosh, 1974; and Siniff et al., 1970), and two major communities have been identified. In one, association with ice is almost obligatory; this group includes the fish, Trematomus borchgrevinki; the birds, Aptenodytes forsteri and Pelagodroma nivea; and the mammals, Hydrurga leptonyx and Lobodon carcinophagus. In the other, association with ice is less strong, but members occur year round in waters strongly influenced by ice; included are the fish, Pleuragramma antarcticum; the birds, Pygoscelis adeliae and Thalassoica antarctica; and the mammal, Balaenoptera acutrostrata. The reasons why these two communities associate with ice and the ways in which the rapid seasonal change in pack ice affect life-history patterns are in need of investigation if the pack ice ecosystem is to be understood. There are many other questions as well. What are the natures of the adaptations, and what unique opportunities does the ice offer so that phagophilic species are able to exploit opportunities in the pack ice? What is the nature of the competitive interactions that may contribute to the distributional patterns of the species within the two major communities? What opportunities does the near-to-ice habitat offer that differ from the ice habitat or from the ocean area not influenced directly by ice? Is the food web and food availability similar for both vertebrate communities?

In addition to the above, the extent to which organic matter transfer processes and rates are influenced by the seasonal ice cover is unknown. In the Arctic, marine mammals and birds feeding in the edge zone of the southeastern Bering Sea encounter different food sources, depending on whether the ice edge overlays the outer shelf (pelagic system) or the middle shelf region (detrital benthic system). This kind of spatial phenomenon could also be important for populations in the Southern Ocean as the edge retreats and grows seasonally, except that the shelf is unusually deep in the Antarctic. Lastly, ideas advanced by fishery oceanographers relating marine fish spawning areas to overall population survival as a function of larval drift through regions of enhanced food supply may have application for krill and other euphausiids. This may be the case particularly in regions like the Weddell Sea, where a large gyre partially encloses the circulation.

Thus studies of consumers in the ice-edge zone must consider not only distribution, abundance, and community composition but also inquiries designed to evaluate organic matter transfer rates and life-history strategies keyed to seasonality and large- and medium-scale physical oceanographic processes.

ICE DYNAMICS

Ice Motion, Interaction, and Deformation

Ice dynamics play an important role in both the large-scale seasonal and smaller-scale synoptic variations of the ice edge. It is likely that these variations influence the location and magnitude of biological activity. This influence may occur indirectly by rapid melting of ice modifying the structure of the upper ocean, or it may occur directly by biological growth attached directly to the ice cover.

On the large scale, ice dynamics modifies the ice mass balance mainly by advection and deformation. In the case of advection, ice motion can transport ice from regions of high growth (such as off the Filchner ice shelf in the Weddell Sea) to regions of rapid melt near the ice edge. In this sense, the ice transport takes on the characteristics of a conveyor belt. In the case of deformation, relative motion creates large amounts of open water. In winter these lead areas greatly enhance ice production, whereas in summer their lower albedo substantially speeds up the decay process (Gordon, 1981). Enhanced ice production in turn produces a much increased salt flux into the ocean, which can increase vertical mixing by overturning and hence modify the nutrient levels near the bottom of the ice. Overturning also carries heat upward, which limits ice growth (Gordon, 1981), and the interaction of the ice with itself can modify the wind-stress transfer into the ocean and hence cause seasonal changes in the oceanic circulation.

On the more localized scale near the ice edge, ice kinematics and dynamics can significantly affect the local environment and hence the biological activity. For example, large synoptic outbreaks of ice past the edge could carry increased biological production into selected regions. The subsequent rapid melt could leave increased biological production in relatively isolated patches far from the main ice edge. It also seems likely the ice interaction plays an important role in upwelling near the ice edge. Specifically, if the ice interacts plastically as assumed in large-scale ice-dynamics models (e.g., Hibler, 1979), it will likely have a rectifying effect on motion near the edge. When on-ice winds occur, the compacted ice cover may resist further compacting, thus creating a variation in wind stress across the ice edge. This variation in wind stress could cause upwelling and an attendant change in biological activity. When off-ice winds occur, on the other hand, ice interaction is likely to be greatly lessened, so that little change occurs in the wind-ocean momentum transfer across the edge. This "cavitating fluid" nature of the ice is a dominant feature of plastic rheologies used in certain large-scale models (Hibler, 1979).

Growth and Decay of Sea Ice

Because of large buoyancy fluxes consisting of either expulsed salt when sea ice forms or freshwater production when it melts, thermodynamic changes in sea ice significantly modify the upper ocean. This decay and freezing process is exacerbated at the ice edge by local dynamics and advection. It is important to establish how this decay and growth are related to ice-edge biological activity and to determine if the rates of growth and decay are critical. In terms of the sea ice itself, it is important to determine the main sources of heat for decay. Is heat primarily absorbed from the ocean, or is it a question of heat loss from the atmosphere and by radiation absorption or as more probable a combination of these factors (Gordon, 1981)? Local measurements of the ice decay rates coupled with oceanographic and micrometeorological measurements can answer many of these questions.

Ice-Edge Oceanography

The dynamics and heat balance of both the atmosphere and ocean combine to determine the ice-edge position and characteristics. The presence of the ice in turn influences the atmosphere and ocean, as well as alters their interaction. Vertical circulation and ice-edge fronts result (Buckley et al., 1971; Alexander and Niebauer, 1981).

A wind field that induces an iceward drift of surface water would instill a two-dimensional circulation near the ice edge. Upwelling over the open ocean and sinking in the ice region could occur if the ocean-atmosphere coupling is reduced in the pack ice. Meltwater confined to the pack ice, and open ocean surface water that may have been heated above the freezing point, would accelerate melting in the pack.

A wind field inducing a seaward drift away from the pack ice would loosen ice concentration and spread meltwater toward the open sea. Possible upwelling may be concentrated within the pack ice, with some relationship to ice concentration.

Therefore, vertical circulation could change sign under different wind conditions. This vertical circulation would cause the polar pycnocline (generally at depths of 100-300 m) to slope in the vicinity of the ice edge. An associated baroclinic current would then develop more or less parallel to the ice edge. Instability of this jetlike current would increase eddy flux of oceanic heat across the ice edge and hence have an impact on the regional ice balance and behavior of the ice edge.

The actual pattern of vertical circulation and the ice-edge front would depend not only on the wind field but also on how the ice changes atmosphere-ocean coupling relative to the open ocean. This in turn depends on the ice concentration gradient near the ice edge and ice roughness. In Arctic conditions, the vertical circulation is of importance in the nutrient balance. Depleted surface-water nutrients are replace by upwelling. This is probably true for stable ice-edge water in the Southern Ocean also. However, the Southern Ocean nutrients are not believed to be a major limiting factor to primary productivity, although local nutrient deficiencies may occur. The vertical circulation in the Southern Ocean may be of greater significance with respect to the ice-edge heat balance, in meltwater distribution, and in the development of ice-edge baroclinic frontal zones, all of which could be expected to have some effect on the ecosystem.

LOCATIONS FOR STUDY

The ice edge is circumpolar, but important variations occur with longitude. In regions with a northward-directed ocean current, the sea ice is advected into lower-latitude promontories. In these positions, the ice injects (by the conveyor belt concept) great quantities of meltwater into regions north of the ice edge. Below the immediate surface water, which "contains" most of the meltwater, is a water column that has experienced ice formation further south. Thus, in these outflow regions, it is expected that the sea ice edge will have its most important impact on the ocean ecosystem.

The best-developed outflow region occurs in the western Weddell Sea. Here a strong northward moving, western boundary current (Gordon, Martinson and Taylor, 1981) carries water from the coast of the Antarctic Peninsula, toward the Bransfield Strait and Southern Scotia Sea. The Weddell water then advects eastward and eventually turns poleward as a broad drift, forming a large cyclonic gyre within the Weddell Basin. This circulation pattern is clearly seen in the sea-ice distribution and water stratification, as heavier ice conditions and colder water invade the southern Scotia Sea and along a latitude band near 60° S further eastward to 20° E.

The ecosystem north of the ice edge in the Bransfield Strait and Southern Scotia Sea is particularly productive. This region is of particular interest in regard to its connection with the sea-ice ecosystem and should be the focus of the ice-edge program.

At least two other regions of the Southern Ocean experience northward advection, where ice influences are carried into the open ocean. Both are less intense than the Weddell situation. One of these regions is north of the Ross Sea continental shelf, where ice and polar water are advected northward and eastward over the southern flank of the midocean ridge; the other occurs over the eastern boundary of the Kerguelen

Plateau. These regions could be subjected to more limited work in a pilot study for a more-extensive Weddell Sea program.

METHODS FOR STUDY AND TECHNOLOGY

General Plan

A sampling grid should be established with the basic aim of determining the spatial and time variations of the ocean and ecosystem characteristics from open ocean to pack-ice condition across the ice edge. It is necessary to begin and end this grid sufficiently far from the ice edge to ascertain the background "far afield" structure. The grid needs to be surveyed under a variety of weather conditions in order to observe the system under a number of oceanic and ice edge states. High-resolution satellite observations of the work area would provide useful regional information.

The grid should extend along as well as perpendicular to the ice edge in order to study mesoscale ocean and ice features. The along-the-edge extent should be about 200 km, depending on biological characteristics found near the ice edge. Satellite observations may be useful in this regard.

The spatial scale of coverage in respect to the ice edge will depend on local characteristics. When the heat balance or the wind and/or ocean current patterns are producing a diffuse ice edge and it is difficult actually to identify the ice edge, observations extending at least 100 km, on either side of the ice edge and possibly to 500 km on the open ocean side of the ice edge may be required. Station spacing would be decreased as the ice edge is approached. Response of the ice-edge characteristics and ecosystem to changing atmospheric conditions requires a station array in time as well as space. Time series observations through ice floes will be needed. These would require a few weeks of measurement from a relatively stationary platform near the ice edge. When a sharp ice edge is present, the observational grid may be more restricted, though more closely spaced observations would be needed.

Physical-Chemical Oceanography Measurements

The physical-chemical oceanographic measurement must define the three-dimensional ocean thermocline and chemical structure relative to the ice edge as well as direct measurement of ocean circulation. Methods are generally well developed, though working in the sea-ice floes requires some special attention to deployment/ recovery and under way measurements.

The ocean thermocline stratification would be measured with a CTD (in situ conductivity-temperature-depth recorder) capable of resolving vertical scales of the order of 0.5 m. Water samples for CTD calibration, nutrient chemistry, dissolved gas, and geochemical parameters should be collected during the CTD oceanographic station. Simultaneous in situ measurement of oxygen and chlorophyll-A should be included with the CTD package.

Between oceanographic stations continuous under way measurement of sea-surface temperature, salinity, and chlorophyll should be made in conjunction with expendable bathythermograph (XBT) observations. The use of towed instrumentation for subsurface measurements should also be explored.

Currents can be measured by profilers, which can yield high-resolution measurements of shear within the water column and by various Lagrangian methods, such as acoustically tracked neutral buoyant floats.

Ice Measurements

Within the observational grid framework, ice kinematics can be monitored by an array consisting of six to eight transponders spread over this region. Their positions can be monitored remotely at about 3 hr. intervals, with triangulation accuracies adequate to resolve inertial oscillation. Simultaneous measurements of the biological activity, ocean structure, and ablation characteristics of the ice can be made over the same Lagrangian region for several weeks. By analyzing these data in conjunction with wind and temperature, it should be possible to sort out rectification effects by ice dynamics near the edge and to get some estimate of the role of local ice dynamics in the decay process near the ice edge. The absence of detailed ice kinematic measurements in previous studies has greatly hampered the analysis of ice-edge processes.

In such measurements it is important to sample accurately enough in time and space to resolve inertial oscillation (occurring at approximately 12-hr intervals). Previous mesoscale deformation measurements (Hibler et al., 1974) have shown these high-frequency motions to comprise a substantial component of deformation, even in relatively compact conditions. Near the edge these oscillations are undoubtedly more pronounced and may be responsible for enhanced decay due to creation of open water. In such a program it is also important to monitor ocean temperature and salinity simultaneously, because advances of the edge may modify the upper ocean structure.

In addition to measuring kinematics at the ice edge, it is important to monitor the drift of the pack ice over a larger region. This can be done most effectively by dropping drifting buoys onto the ice and then monitoring position and atmospheric pressure by satellite. In the winter before the planned field program, an array of about five buoys could be deployed. These would allow the larger scale motions to be tracked before disintegration of the ice edge and greatly aid in improved atmospheric analysis for ice-drift calculations. At least two buoys should be deployed in regions where the ice is expected to last far into the melt season, so that they operate during the field program at the edge.

Vertebrate and Food-Web Studies

To estimate characteristics of vertebrate communities, line transects along fixed tracks are desirable. These should intersect the ice edge or other frontal systems at approximate right angles beginning in open water a substantial distance from the edge and terminating well into the ice pack (or vice versa). A parallel series of such tracks extending many kilometers along the edge and spaced about 50 km apart would be desirable. The actual length and spacing of transects would, in part, be subject to the biological activity observed. The ship should cruise at 6-10 knots, and tracks should be integrated with oceanographic stations. The grid described above under General Plan would be excellent design.

During oceanographic stations and in conjunction with the time-series measurements from ice floes, food-web data should be collected. Collections of birds and seals, vertical trawls for zooplankton, and jigging for squid would help to determine the feeding selectivity. Acoustic surveys of fish, squid, and krill should occur along all transects.

Satellites

Satellites are an extremely valuable tool for monitoring the large scale changes of the ice edge; most charts of the edge rely heavily on satellite imagery. Passive microwave sensors detect changes in ice concentration and the presence of ice by surface emissivity characteristics. Their most notable advantage is that they are not affected by cloud cover. Other important sensors are visual imagery and the (VHRR) satellites employed by both NOAA and the Air Force (the latter are often referred to as DMSP satellites).

At present, there is only one passive microwave satellite in operation in the NIMBUS series. The present system employs a SMMR; unfortunately, the lifetime of this system is only about one year. It was supposed to have been followed by the NOSS satellite, but that program has been canceled. The next planned satellite employing passive microwaves is RADARSAT, which is planned for the late 1980's as a joint U.S.-Canadian venture. Although somewhat hampered by cloud cover, imagery from the DMSP and NOAA satellites will continue to be available.

Ice Position and Deformation Technology

Three main ways exist to monitor ice motions: (a) satellite positioning usually of air-droppable remote buoys, (b) line-of-sight radar positioning of transponders, and (c) optical line-of-sight techniques employing either theodolites or lasers. The satellite-positioning methods employing remote buoys are valuable for automated long-term measurements. They are, however, somewhat limited in resolution (several hundred meters), and sampling can be rather sparse in time depending on the satellite employed for readings. Transponders are much more accurate (within 1 m) and do have all-weather capability but are limited to line-of-sight measurements. They are, however, valuable for short-term, detailed measurements (over several weeks) of the ice kinematics over a region about 30 km in diameter. The transponder system is computer controlled and can be programmed to make measurements automatically at any required time interval. The optical systems are the simplest to use but are affected by blowing snow, fog, and low-lying clouds. They also require more intensive manpower and are usually limited to about a 10 km radius. Optical methods are accurate to distances of $\pm$ 5cm.

Very High-Frequency Acoustic Sampling Technology

Active acoustic methods to census fishes, squid, and large zooplankton/micronekton species have found application in ecosystem studies (BIOMASS, PROBES). These systems generally operate from transducers fixed in a ship's hull or from towed bodies operating below the surface. For reasons associated with signal attenuation, frequencies above 400 kHz are not used routinely. Some recent work in the megahertz frequency range (R. Pieper) demonstrates that small targets, about 1.0 mm, can be censused successfully but at reduced ranges (a few meters). This means that at very high frequencies the transducer must be side-looking and lowered through the water column.

The opportunity to mate such a system with a conductivity-temperature-depth recorder and fluorometer should be seriously considered for work in the pack ice, where routine net towing is difficult at best. Such a system would provide real-time vertical profiling of physical structure (temperature, salinity), plant pigments, and small grazers in a manner now impossible with conventional sampling methods. These measurements would supplement down-looking acoustic sampling designed to census micronekton and fishes in the same water column.

Ships

From the previous suggestions it is obvious that a successful ice-edge research program depends on a mobile platform and possibly two platforms working together. In the near future, Coast Guard icebreakers, UNOLS vessels, or vessels leased from other nations will have to be used, but, eventually the United States should provide a polar-ice-strengthened research vessel if it is to play a significant role in high-latitude oceanographic research. Given that ice-covered seas are critical to the Antarctic ecosystem, this need becomes compelling. At present, the United States does not possess even one such vessel. Rather than allowing this to constrain research, it is important that programs be developed and implemented using available facilities, pending the availability of a dedicated platform. Such a ship, if well designed, will be primarily an oceanographic research ship and should be suitable for use in open water as well as pack ice and therefore could support a significant portion of the U.S. Antarctic marine research program.

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Appendix E. 2:
Aggregations of Krill — Recommendations for Research

Report of a Workshop Held at

Woods Hole Oceanographic Institution

April 13 - 14, 1981

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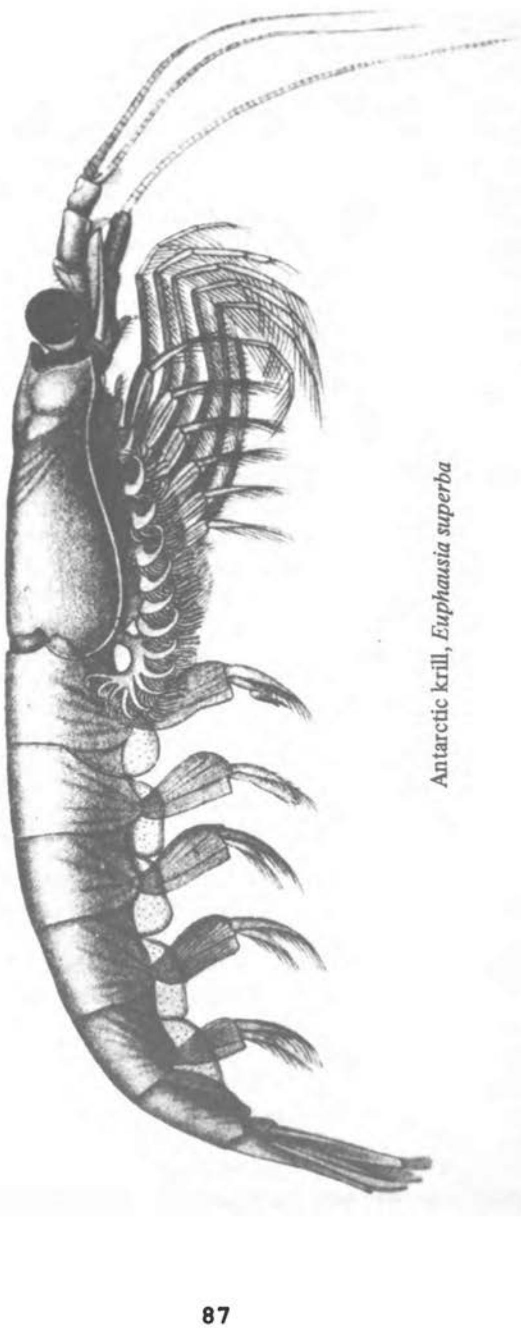

Antarctic krill, *Euphausia superba*

INTRODUCTION

As noted in the main report, understanding of the causes and consequences of aggregations of krill--particularly those dense aggregations termed swarms or schools is critical to the understanding of the dynamics of krill (or euphausiid) populations, the ecology of the predators that depend on these aggregations for food, and the management of both krill and predators in the face of anthropogenic impacts.

An excellent summary of the problems, and of the existing literature, is given by J. Mauchline, 1981, Studies on Patches of Krill, Euphausia superba Dana, BIOMASS Handbook No. 6.

The Working Group on Understanding the Basis for Krill Aggregation reviewed recent observations on swarming of the euphausiid, Meganyctiphanes norvegica, at the mouth of the Bay of Fundy (S. Nichol, C. Boyd); results of acoustic and net sampling from the R/V Melville during FIBEX (M. Macauley; E. Shulenberger); and observations by Japanese scientists while on commercial vessels (conversations reported by W. Hamner). There was also a discussion by W. Hamner and P. Major of the evolutionary advantages of aggregation and its behavioral elements in predator/prey systems.

It became clear that there are several types of swarms and therefore probably several causes or stimuli for the swarming. The following contrasts were indicated by comparison of specific cases: (1) swarms (or schools) apparently associated with island or continental shelves such as those in the Scotia Arc versus those in the open ocean over deep water such as in the Indian Ocean sector (though these may be associated with mesoscale hydrographic features); (2) swarms of sexually mature krill (sometimes strongly biased toward one sex) versus swarms or aggregations of larval or juvenile individuals; (3) swarms concentrated at the surface, sometimes in broad daylight, versus permanently subsurface swarms; (4) swarms that have lifetimes of many days (though this does not necessarily mean that all individuals remain in the swarm for its full duration) versus ephemeral swarms.

It is not clear that all possible combinations exist; for example, we know of no reports of surface swarms, or of fully organized schools, of larval krill. Searches for a single explanation for all swarming events may well be futile.

The working group was also concerned lest the focus of research on swarms result in the neglect of other problems. For example, the acoustic surveys indicate that the majority of individual krill at any given time may not be living in aggregations as dense as swarms and schools, though their distribution is patchy in a statistical sense. Also, we are woefully ignorant of the seasonal biology of krill. We know little about the intensity of swarming in seasons other than austral summer or about events under the winter ice. We also need to know much more about seasonal variations in reproduction and early larval life.

PROBLEM IDENTIFICATION

The working group discussed three general types of problems that may require for their solutions quite different types of cruises and facilities: (1) Proximal causes of the various kinds of swarms and schools, involving measurement of environmental and behavioral parameters associated with swarms and eventual elucidation of the necessary stimuli leading to their formation and breakup. This work should lead to ability to predict the conditions in which swarms will be found. It may be useful to realize that other species of Antarctic zooplankton also form dense aggregations. (2) Ultimate or evolutionary causes for swarming and schooling. This is a purely biological issue and requires careful observations under controlled or manipulated conditions of the behavior of individual euphausiids and of the behavioral interactions between krill swarms and predators. This line of investigation may require a large, land-based tank and may not be immediately feasible. (3) Seasonal and reproductive biology of krill populations, requiring the ability to make measurements and take samples under conditions where surface ships cannot be used. This same ability would, of course, greatly increase spatial coverage even in those seasons when surface ships can be operated.

RESEARCH RECOMMENDATIONS

We recommend several research programs directed at the solution of these problems. It is worth pointing out that, as recommended by the parent committee, the research of U.S. scientists should complement but not necessarily duplicate the efforts of other nations. The major U.S. contribution to the international effort may be to develop and demonstrate the usefulness of high-resolution acoustic systems capable of determining the abundances and individual sizes of krill that are not aggregated, those that are in small swarms and schools (at most a few tens of meters in horizontal extent), and those that are in aggregations large enough to be commercially attractive.

We also believe that prediction and management must, to be successful, rest on fundamental understanding. We therefore concentrated on obtaining such understanding rather than on specific managerial issues.

Program 1. Relation of swarms to physical oceanography. We start from the presumption that acoustic systems can now be made to distinguish swarms of krill from other features. We recommend three scales of study:

(a) Time series of transects across the Drake Passage, primarily using expendible bathythermographs and acoustic detection of swarms, to be done from ships in transit for other reasons. This will require that all transiting ships be equipped with adequate (and intercalibrated) acoustic systems.

(b) Repeated (perhaps weekly) short sections of conductivity-temperature-depth recorder and in situ fluorometer lowerings plus acoustic data in one or two areas of high probability of encountering swarms. Special attention should be paid to the presence of hydrographic rings and eddies, which could reduce the transport of krill out of the area.

(c) Bottom-mounted, upward-looking, untended acoustic systems and associated thermistor strings to determine the frequency of swarms of all sizes at a few locations over several months.

Program 2. Description of large swarms and their behavior. This program requires opportunistic cruise planning. Instead of determining a specific number of stations or a geographical area to be covered, the object will be to find a large swarm and spend considerable time observing and sampling it. Ideally, two ships would cooperate; one would repeatedly map and track the swarm acoustically and measure standard environmental parameters. The water in which the patch originally is found should be tagged at several depths by drogues and/or dye such that vertical shear and differential movement of water and krill can be measured. The other ship would deploy a variety of observational and sampling tools to reveal the behavior and condition of euphausiids within the swarm. These tools should include opening/closing nets and trawls of several mesh sizes and speeds of tow; acoustic systems permitting very high spatial resolution (megahertz, dual beam); towed or free-fall stereo camera systems capable of operating down to 100 m; a low-light video system; and (where feasible) divers. The object is to describe the internal dynamics, individual spacing, presence or absence of feeding and/or breeding, and other characteristics of euphausiids in swarms. The important thing is to retain considerable flexibility and variety in observational capabilities. Different techniques integrate over different spatial scales and are therefore complementary.

Over several years, swarms or aggregations of both adults and juveniles should be studied. The younger stages are easier to sample quantitively but may have less social behavior.

Program 3. Seasonal biology of krill and of swarms. Data on spatial and temporal distributions of krill are at present limited to the ice-free season and must be supplemented by observations at other seasons. This is not because the krill will be harvested in austral winter but because the ability of the stock to tolerate harvesting or adverse anthropogenic impact from hydrocarbon exploitation depends on the stock's reproduction, growth, and "natural" mortality. These rates may change during the nonharvesting season as a result of changes in population size due to previous harvesting; if so, the nature of these changes must be understood.

The most elementary question is to ask whether krill are present beneath the ice during winter in areas where swarms are present in summer. If they are not, where have they gone? To answer this will require robust and reasonably inexpensive bottom-moored sampling systems (probably multifrequency acoustic but perhaps also stereo photography), which can record abundances of krill under the ice or in open water periodically (limited by power) through the winter. If krill have a unique "signature" of bioluminescence, this could also be recorded.

Reproduction, molting, and (from the molts) size composition could be assessed from the catches of large sediment traps that would retain sinking eggs and molts in preservative. Catches of fecal pellets (if any) will give an indication of the winter food. These traps should inject periodic time marks (e.g., a layer of artificial particles) so that history of the collection can be reconstructed. This could, of course, also be done during open-water seasons.

Moorings to measure physical parameters (currents, temperature, perhaps salinity, and O_2) should be located near the biological moorings.

More complex questions of interactions between krill and ice, such as the possibility of direct feeding by krill on algae growing on the underside of the ice, will probably require direct observation and/or collection of living animals immediately under the ice. It should also be pointed out that relatively long-term maintenance of captive krill may be necessary to determine fecundity, larval growth rates, and other features.

Finally, additional collections in deep water with relatively fine-meshed, opening/closing nets are needed to refine our impressions of the depths and locations at which spawning and hatching of eggs occur.

EPILOGUE

We have proposed a combination of research programs that will be expensive not only because of the time required on large ships but also because of the relatively large (for biology) investment required in the development of equipment. We do not believe that the proposed research will be sufficient for the full understanding of krill populations nor for their management. We are, however, convinced that these programs are <u>necessary</u> for understanding and management.

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Appendix F:
Antarctic Marine Ecosystem Research: Selected Bibliography*

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