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ANTARCTIC MARINE ECOSYSTEMS RESEARCH; WHERE TO FROM HERE ?

Sayed Z. EL-SAYED

Department of Oceanography, Texas A & M University, College Station, Texas 77843, U.S.A.

Abstract: The initiation of the Biological Investigations Of Marine Antarctic Systems and Stocks (BIOMASS) Program in the late 1970s has provided several important insights into the functioning of the Southern Ocean ecosystems and has helped in creating a climate in which research programs addressing elements of the general and specific objectives of BIOMASS were able to flourish. This has led to an explosion of marine research programs to study phenomena and processes of global significance in which Antarctica and the surrounding seas play a key role.

While the BIOMASS Program dealt primarily with practical problems related to the wise management of marine living resources of the Southern Ocean, the program addressed neither environmental issues nor problems related to the biogeochemistry of the Southern Ocean. These were left to the other more focused, process-oriented programs which were developed in response to the worldwide concern over climate change as a result of increased levels of CO_2 and the depletion of the stratospheric ozone over Antarctica. This concern has provided the stimulus behind such programs as the Southern Ocean-Joint Global Flux Study (SO-JGOFS), and the Southern Ocean-Global Ecosystem Dynamics (SO-GLOBEC) which regarded the Southern Ocean as an ideal environment in which to test many of the hypotheses put forward by these programs.

A few of the programs that have a focus on Antarctic marine ecosystems and their living resources are discussed, and their contributions to a better understanding of the Antarctic marine ecosystems are evaluated.

1. Introduction

Research in the Southern Ocean until recently has mainly dealt with the study of the Antarctic marine ecosystem, its living resources as well as its hydrographic features. In recent years, however, with the worldwide awareness over climate change as a result of increased levels of carbon dioxide, the depletion of stratospheric ozone, there has been a shift towards programs which address global problems and which can best be accomplished in the Antarctic. As a result we have witnessed the initiation of several scientific programs, *e.g.*, Southern Ocean-Joint Global Flux Study (SO-JGOFS) and Southern Ocean-Global Ecosystem Dynamics (SO-GLOBEC), to study phenomena and processes of global significance in which Antarctica and its surrounding seas play a key role. These and similar programs have rightly identified the Southern Ocean as a region meriting special attention.

In this paper a few of the programs that have a focus on Antarctic marine ecosystems and their living resources are discussed and their contributions to a better understanding of the Antarctic marine ecosystems evaluated. However, before we discuss these programs, it would be useful and instructive to discuss briefly some of the unique physical, chemical and biological features of the Southern Ocean. After all, it is these features that have stimulated the interest of the scientific communities and provided them with major opportunities to expand fundamental knowledge on global issues as climate change, ocean circulation, ocean productivity, and pollution.

2. Unique Features of the Southern Ocean

The Southern Ocean, defined as that body of water south of the Subtropical Convergence, covers nearly 20% of the World Ocean. It has several unique features that separate it from the other oceans; these are: (a) the presence of pack-ice around the Antarctic continent and its seasonal waxing and waning; (b) variability of the light regime which, south of the Antarctic Circle, alternates between continuous darkness in winter and continuous daylight during the summer; (c) the circumpolarity of the Antarctic waters and the formation of Antarctic Bottom Water; (d) high concentrations of inorganic nutrients; and (e) extensive cloud cover. A few of these unique features are discussed below.

2.1. Pack-ice

Pack-ice is one of the dominant physical features of the Southern Ocean; it provides one of the major habitats for organisms from bacteria to marine mammals. It's seasonal waxing (about $20 \times 10^6 km^2$ in winter) and waning (about $3 \times 10^6 km^2$ in summer) give rise to important physical effects through the modification of heat flux between the atmosphere and ocean. Its interannual variability has major impacts on all levels of the marine ecosystems. According to KNOX (1994), "Pack-ice has a dramatic effect on all aspects of environmental variation in that is affects the magnitude of fluxes of heat, gases and matter to and from the atmosphere; plays a key role in CO_2 fluxes; has a dominant influence on structure of the water column, nutrient concentration, primary production and sedimentation; and supports a unique and tightly coupled biological community". For these reasons, understanding the dynamics and thermodynamics of this system is critical for understanding the role of Antarctica in climate change and world ocean circulation.

2.2. Hydrography

The Southern Ocean is the site for the formation of water masses (*e.g.* Antarctic Bottom Water and Antarctic Intermediate Water) whose influence extends far beyond the Southern Ocean itself.

One of the most important processes that is uniquely "Antarctican" is ocean ventilation, *i.e.*, the process by which the deep ocean affects the atmosphere on a time scale of decades to centuries. This ventilation (or overturning) can affect climate change by delivering heat to the atmosphere and drawing down CO_2 into the deep ocean for long-term storage which reduces the "greenhouse effect".

2.3. Biology

The Southern Ocean represents an "oceanic enigma" in the carbon cycle. It is the largest High Nutrient-Low Chlorophyll (HNLC) region in the World Ocean. This has given rise to the so-called "Antarctic Paradox" which can be explained as the apparent inability of the phytoplankton to utilize the high nutrient concentration (EL-SAYED, 1987). As a result the Southern Ocean exhibits a mismatch between primary production by phytoplankton and the availability of inorganic nutrients.

Further, the Southern Ocean phytoplankton plays a significant role in the global carbon balance and in regulating global climate. The absorption of a large fraction of CO_2 by marine phytoplankton, through the process of photosynthesis, lowers the concentration of CO_2 in the surface waters and helps in the drawdown of atmospheric CO_2 to the ocean surface through gas exchange. Understanding this carbon balance is important to understanding the formation of atmospheric CO_2 and its contribution to the "greenhouse effect". Moreover, Antarctic phytoplankton play another important role in global climatic change. It has been calculated that up to 10% of the global flux of dimethyl sulfide (DMS) to the atmosphere emanates from the Southern Ocean where the Prymnesiophyte alga *Phaeocystis pouchetti*, which occurs in exceedingly plentiful concentrations in Antarctic waters (*circa* 10^7 cells/L), is reportedly the principal source of this gas. The oxidation of DMS forms sulfide aerosol particles which promote the development of clouds and thus influence climate.

The depletion of stratospheric ozone over Antarctica has led to increased ultraviolet flux to the surface waters of the Southern Ocean during austral spring/summer. The effects of UV radiation on marine ecosystems is at present a major focus of research in Antarctica. Suffice it to say that increased levels of UV have been shown to affect photosynthetic activity, cause decrease in growth and metabolic rates, impair nitrogen assimilation, increase mutagenesis in DNA, bleach the photopigments and bring about changes in the species composition and alter community diversity (see EL-SAYED *et al.*, 1996).

3. Overview of Research Programs with Focus on Antarctic Marine Ecosystems and Their Living Resources

The initiation of the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) Program in the late 1970s has contributed several important insights into the functioning of the Southern Ocean ecosystems, and has helped in creating a climate in which research addressing elements of the general and specific objectives of BIOMASS were able to flourish (EL-SAYED, 1994). While the BIOMASS Program dealt primarily with practical problems related and the wise management of marine living resources of the Southern Ocean, in particular krill, the program addressed neither environmental issues nor problems related to the biogeochemistry of the Southern Ocean. These were left to the planners of the other more focused, process-oriented programs which were developed later in response to the worldwide concern over climate change as a result of increased levels of CO_2 and the depletion of the stratospheric ozone over Antarctica. This concern has provided the stimulus behind such programs as the SO-JGOFS, and SO-GLOBEC which regarded the Southern Ocean as an ideal environment in which to test many of the hypotheses put forward by these programs.

What follows is an overview of the research programs that have a focus on the Antarctic marine ecosystems and their living resources. We will begin with the BIOMASS Program, this will be followed by discussing other programs beginning with those dealing with the primary producers and then moving up the trophic ladder to programs that address the top predators in the ecosystem.

3.1. Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS)

The main objective of the BIOMASS Program is "*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*" (El-Sayed, 1977).

The history and accomplishments of the BIOMASS Program have been published in "*Southern Ocean Ecology: The BIOMASS Perspective*" (El-Sayed, 1994), and will not be discussed in detail here. Suffice it to say , though, that within its relatively short life span BIOMASS has accomplished the following:

- Provided several important insights into the functioning of the Southern Ocean ecosystems which were incorporated in global change studies.
- Provided a description of the distribution and biology of krill which probably could not have been obtained without the coordinated efforts and standardized techniques employed during the Second International BIOMASS Experiment (SIBEX) phase of the Program.
- Through its expertise of establishing multi-national collaborative programs, and through the existence of appropriate "infrastructure", BIOMASS was instrumental in shaping up subsequent programs of global change research in the Antarctic.
- Established in 1985 the BIOMASS Data Center, which is probably the first international relational database in biological oceanography.
- The Program assisted in establishing an international marine science community without which the development of CCAMLR (see below) would have been impossible.
- The Program fostered international scientific cooperation, particularly through the simultaneous, multi-ship surveys.
- BIOMASS rekindled great international interest in Antarctic affairs reminiscent of the International Geophysical Years.

3.2. Medium-term programs (5–10 years)

3.2.1. Programs addressing low trophic levels

A. Antarctic Marine Ecosystem Research at the Ice-Edge Zone (AMERIEZ)

This multidisciplinary investigation of the pelagic ecosystems and processes was designed to build upon previous research at the marginal sea-ice zone (Sullivan and Ainley, 1987). Its two unifying hypotheses are: (a) that the pack-ice edge is a major oceanographic feature characterized by increased biomass and biological production, and (b) that the seasonal advance and retreat of the ice margin strongly affects the natural history of most of the organisms in the vicinity (Sullivan and Ainley, 1987). AMERIEZ concentrated on seasonal ice edge dynamics through a series of research cruises to the marginal ice-edge zone of the Weddell Sea during austral spring (1983), austral autumn (1986) and austral winter (1988). Hallmarks of the program have been its truly interdisciplinary approach, and the incorporation of satellite remote-sensing imagery to define the mesoscale variability and dynamics of the ice-edge zone.

B. Research on Antarctic Coastal Ecosystem Rates (RACER)

In 1981, the U.S. National Research Council/Committee to Evaluate Antarctic Marine Ecosystem Research identified the Coastal Zone of the Antarctic Peninsula as one of several Antarctic marine ecosystems needing comprehensive, interdisciplinary study. The coastal shelf region is thought to be especially important because it supports an extensive Antarctic spring bloom of phytoplankton, has a high annual rate of primary production, and is a principal feeding and spawning ground for Antarctic krill (HEMPEL *et al.*, 1979; ROSS and QUETIN, 1982; BRINTON *et al.*, 1986). However, the processes responsible for the biological richness of this system are not well understood, and comprehensive data on microbial rates and element cycling in the Antarctic Peninsula region are relatively few (KARL, 1991). Furthermore, the simple diatom/krill/whale food chain (HART, 1942) was brought to question with the realization that much of the phytoplankton crop could not be utilized directly by krill (VON BROCKEL, 1981).

Although the Southern Ocean is reknown for massive blooms of large celled diatoms (HART, 1942), most of the primary production and biomass is contained in the nanoplankton fraction (HASLE, 1969; Fay, 1973; HEWES *et al.*, 1985, 1990). This led HEWES *et al.* (1985) to suggest that other predator-prey interactions below the "krill food-chain" occurred, so that primary production that occurred in particles too small for krill could be transferred by an intermediate grazer step, namely the protozoan "herbivores". It has been shown that less than 10% of primary production goes into the bacterial pools (AZAM *et al.*, 1991; KARL *et al.*, 1991) that might be recycled upwards via the "microbial loop" (AZAM *et al.*, 1983). Since Antarctic phytoplankton populations do not appear to be nutrient limited in general, the importance of bacterioplankton as remineralizers of exudation is probably less important than in other waters (HEWES *et al.*, 1985; AZAM *et al.*, 1991)

The two central hypotheses of the RACER Program are:

1. Stability-Productivity Hypothesis, states:
   Upper-ocean physical dynamics control productivity at all levels of the food web and that productivity is significantly greater in near shore stratified waters than in the offshore region.
2. Island Effect-Residence Time Hypothesis, states:
   Islands and irregular bottom topography interrupt the flow of water onto the coastal shelf, thus increasing mean residence time and allowing for greater productivity there than in offshore regions.

To address these hypotheses and their ecological implications, an interdisciplinary group of scientists conducted comprehensive summer study of coastal processes in the western Bransfield Strait (1986–87) and Gerlache Strait (1989) and in subsequent years revisited the study area and expanded their temporal (austral winter) and spatial coverage.

Investigators combined studies of upper-ocean physics, photobiology and bio-optics, microbiology, particle flux, and the distribution and physiological rates of krill, zooplankton and nekton (KARL *et al.*, 1991). These and other similar studies are currently the focus of other countries national programs; notable among these are the investigations carried out on board the *Polarstern* (Germany), the *James Clark Ross* (U. K.), the *Aurora Australis* (Australia), the *Kaiyo Maru* (Japan), to name a few.

C. Southern Ocean - Joint Global Ocean Flux Study (SO-JGOFS)

SO-JGOFS is sponsored by SCOR, with co-sponsorship of SCAR. SO-JGOFS is a core project of the International Geosphere-Biosphere Program (IGBP). JGOFS was established in an attempt to quantify the flux of CO_2 to and from the oceans, and to describe the physical, chemical and biological processes involved.

JGOFS has identified the Southern Ocean as a key research site for studying these processes. The Southern Ocean study will attempt to describe contemporary carbon pools and fluxes, and their controlling factors, with a view to being able to predict the effects of climate change. However, before a model of the Southern Ocean carbon fluxes can be made, the present magnitudes of carbon fluxes must first be evaluated. This will require a systematic description of the spatial and temporal variability of CO_2 fluxes, and identification of the key environmental and biological factors which regulate these fluxes.

The objectives of SO-JGOFS could be defined by a number of key questions (SCOR, 1992):

- *What role does the Southern Ocean play in the contemporary global carbon flux ?*
- *What controls the magnitude and variability of primary production and the fate of particles ?*
- *What are the major features of spatial and temporal variability in the physical, chemical and biological environments ?*
- *What is the effect of sea-ice on carbon flux in and out of the Southern Ocean ?*
- *How has the role of the Southern Ocean changed over geological time-scales ?*
- *How might this role change in the future ?*

D. Coastal and Shelf Ecology of the Antarctic Sea-Ice Zone (CS-EASIZ)

CS-EASIZ is a 10 year research program under the auspices of SCAR Group of Specialists on Southern Ocean Ecology. Its objective *is to improve our understanding of the structure and dynamics of the Antarctic coastal and shelf ecosystem which is recognized as the most complex and productive ecosystem of Antarctica and likely the most sensitive to global environmental change.*

The Program will focus on those features that make the biology of this ice-dominated ecosystem so distinctive, and on understanding seasonal, inter-annual, and long-term changes. The unique character of CS-EASIZ is its coherent approach to the ecology of the coastal and shelf marine ecosystems by integrating work on the ice, water-column and benthic sub-systems.

The core of the program will be a series of basic measurements to be undertaken on the ice, water-column and benthic sub-systems of the Antarctic coastal and shelf ecosystem (SCAR, 1994).

3.2.2. Programs addressing higher trophic levels

A. Southern Ocean Global Ocean Ecosystem Dynamics (SO-GLOBEC)

SO-GLOBEC is sponsored by SCOR, with co-sponsorship of SCAR, IOC, ICES and North Pacific Marine Science Organization. It has recently been accepted as a core project of IGBP. The program is dedicated to understanding the effects of the physical processes on predator-prey interactions and population dynamics of zooplankton and their relation to ocean ecosystems in the context of global climate system and anthropogenic change (GLOBEC, 1994). The main objective is *to understand the linkage between physics and biology on different scales, from ocean scales to meters and decimeters.*

The program is targeting two groups of organisms for study: zooplankton (copepods, krill and salps) and top predators (seals and penguins). Its activities consists of two field studies (winter and summer, six months each) and modeling activities that will be supported by strong data management. The summer study will focus on foraging, reproduction and recruitment; whereas the winter study will focus on overwintering strategies.

SO-GLOBEC will concentrate on three principal areas: (a) Antarctic Peninsula region, (b) Eastern Weddell Sea, and (c) Indian Ocean Sector.

Model development will include: (a) a conceptual model of the ecosystem, (b) circulation models, (c) biological models (GLOBEC, 1994).

B. Antarctic Marine Living Resources (AMLR)

The US/NOAA-sponsored AMLR Elephant Island Study began in 1984. Its central goal is to describe the functional relationships between Antarctic krill, their food-base, their predators, and the key environmental variables. The field research program is designed to address two main hypotheses: a) Krill predators respond to changes in the availability of food, and b) Distribution of krill is determined by physical, chemical, and biological characteristics of the pelagic habitat (Holt *et al.*, 1991). AMLR maintains an annual ecosystem study which focuses on trophic linkage in the vicinity of the Elephant Island.

The Program also supports some aspects of seabird research in the Palmer Long Term Ecological Research (LTER) study region (see below).

C. CCAMLR Ecosystem Monitoring Program (CEMP)

The atmosphere of international collaboration created by the BIOMASS Program, together with the growing interest in the conservation of the Southern Ocean ecosystems and their living resources and the need for coordinated international management of Antarctic marine resources, have spurred the Antarctic Treaty System to establish the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) which was ratified in 1982 (Croxall, 1994).

It has been correctly pointed out that CCAMLR had its foundation in BIOMASS, as both are rooted in their concern over the development of a sound ecological strategy for the exploitation and conservation of the living resources of the Southern Ocean (Everson and Miller, 1994). BIOMASS was very influential in ensuring that the Convention maintained a holistic, ecosystem perspective, an approach that is unique in the field of marine resources management. According to this approach, exploitation of a resources should not be allowed to progress to the point at which non-target species are at risk. Further, CCAMLR wisely focused not only on the complex relationships of Antarctic marine living resources with each other, but on their physical environment as well. CCAMLR has developed its own Ecosystem Monitoring Program (CEMP) which has been running for several years and which focuses on local effects of krill abundance on top predators. The program is designed to monitor the status of

Antarctic marine ecosystems through an international collaborative research program. It relies on standardized methods to selected species and sites as a means of collecting reliable long-term data series (IWC, 1996). Recently, CEMP began to add sea-ice data to its routine measurements. CCAMLR monitoring activities are focused on the areas of commercial harvesting, three Integrated Study Regions (South Georgia, Antarctic Peninsula and Prydz Bay) and a network of monitoring sites.

3.2.3. Programs addressing upper trophic levels

A. Antarctic Pack-Ice Seals (APIS)

APIS is an international research program coordinated by the SCAR Group of Specialists on Seals. Antarctic pack-ice seals are thought to comprise up to 80% of the world's total biomass of seals. Like most of Antarctic baleen whales, pack-ice seals are highly dependent on krill for food. As top predators, they play a key role in monitoring shifts in ecosystem structure and function in response to human activities and global climate change. The broad objectives of the program are "*to examine trends in the distribution and abundance of pack-ice seals and the causes and consequences of these trends at a wide range of spatial and temporal scales*" (IWC, 1996).

The program focuses on the ecological importance of pack-ice seals in the Antarctic marine ecosystem by assessing their population abundance and distribution and by understanding the process of energy and carbon flux through their foraging and respiration within the Antarctic ecosystem.

The five-year program will focus on the following regions: The Bellingshausen Sea, Antarctic Peninsula and South Shetland Islands, Weddell Sea, Prydz Bay, and Ross Sea.

3.3. Long-term programs (>10 years)

A. Long-Term Ecological Research (LTER)

Because of the potential role of the Antarctic waters in global biogeochemical models, they have been selected as one of several habitats for conducting a major process-oriented JGOFS research. In 1990, an LTER site was established at Palmer Station by the National Science Foundation in recognition of the need to study ecological processes that occur over long time spans. The research area comprises a $900 \times 200\ km^2$ region along the western coast of the Antarctic Peninsula.

The central hypothesis of Palmer LTER is that *interannual variability in the annual extent of the pack ice has major impacts on all levels of the marine ecosystem.* One of the objectives of Palmer LTER is "*to assess the impact of this variability on representative species of the marine pelagic ecosystem in the region west of the Antarctic Peninsula*" (HOFMANN *et al.*, 1996).

A central tenet of the Palmer LTER is that the annual advance and retreat of sea-ice is a major physical determinant of spatial and temporal changes in the structure and function of the Antarctic marine ecosystem, from total annual primary production to breeding success of seabirds.

The Palmer LTER focuses on the pelagic ecosystem in Antarctica and the ecological processes that link the extent of the annual pack-ice to the biological dynamics of different trophic levels. The LTER consists of six components that focus on:

- Primary production and bio-optical modeling of primary production.
- Phytoplankton and nutrient dynamics.

- Distribution, abundance and ecological physiology of secondary producers, in particular krill.
- Seabird population dynamics and reproductive ecology.
- Dissolved organic carbon and microbial processes.
- Hydrography, coastal circulation and physical modeling.

B. Living Marine Resources Module of Global Ocean Observing System (LMR-GOOS)

GOOS is a joint activity of the Intergovernmental Oceanographic Commission (IOC), World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), and was initiated by IOC in 1989.

GOOS is the designation of a long-term ocean observing system that is presently being developed. GOOS is intended "*provide a global framework or system for the gathering, coordination, distribution and the generation of derived products of marine and oceanographic data of common utility to a full spectrum of user groups*" (IOC, 1996). GOOS has been defined in terms of five modules:

- Climate monitoring, assessment and prediction.
- Monitoring and assessment of marine living resources.
- Monitoring of the coastal zone environment and its changes.
- Assessment and prediction of the health of the ocean.
- Marine meteorological and oceanographic operational services.

The objectives of LMR-GOOS module are *to design and implement a system of observation, data assimilation and modeling to monitor and predict the state of the marine ecosystem at regional and global scales.* Special emphasis will be laid on those features of the living marine resources that are of economic, social and environmental importance (SCOR, 1996).

One of LMR-GOOS premises is that many aspects of the biology of the ocean and the interconnected shelf seas tend to be related on very large scales. According to the LMR concept, some local or regional variations may only be explained by examining events distant in time and space. LMR-GOOS provides the opportunity to take account of large-scale spatial and temporal interconnections (SCOR, 1996).

It is envisaged that the LMR module will include the development of a system to monitor physical, biological and chemical variables needed to describe the structure and functioning of marine ecosystems as well as the changes in these ecosystems over various space and time scales (IOC, 1996). The global scale of LMR is essential because many significant processes and events are decadal in time scale and ocean basins are larger in space scale. Changes in biological regimes are known to take place over years to decades, with space scales and teleconnections over thousands of kilometers. These events and changes can only be monitored and detected if the framework of LMR-GOOS is global.

C. Global Change of the Antarctic (GLOCHANT)

GLOCHANT is a program under the auspices of SCAR Group of Specialists on Global Change and the Antarctic. GLOCHANT is not a research project *per se*; rather it is a communication/coordination project. The project was set up to oversee a major, new long-term program with six core projects addressing broad interdisciplinary topics which are central to global change studies. These core projects are:

- Antarctic sea-ice.
- Global palaeoenvironmental records from the Antarctic sheet and marine and land sediments.
- Antarctic mass balance and sea-level change.
- Antarctic stratospheric ozone and ultra-violet effects.
- Role of the Antarctic in biogeochemical cycles.
- Detection of global changes in the Antarctic.

Within the framework of GLOCHANT, a new program, ASPECT (Antarctic Sea Ice Processes, Ecosystems and Climate), was developed. ASPECT is a multi-disciplinary Antarctic sea-ice zone research program specifically designed to address the deficiencies in our understanding of the key problems in the sea-ice zone, and to complement existing research programs in the region, while carefully avoiding duplication (SCAR, 1996). The ASPECT program aims at:

- *defining a framework of the priority Antarctic sea ice zone research required to address global change and related issues.*
- *promoting and fostering coordinated contributions to this plan from within national research programs and by building on ongoing projects.*
- *liasing with other international programs requiring data and research products from the Antarctic sea-ice zone.*
- *convening workshops.*

4. Summary of Current Research Programs and Their Foci

I. MEDIUM-TERM PROGRAMS (5–10 YEARS)

A. Low Trophic Levels (AMERIEZ, RACER, SO-JGOFS, CS-EASIZ)
The focus of these programs is on measurement of CO_2, dissolved and particulate organic carbon, primary production (and export), single-cell organisms, water-column processes and physics.

B. Higher Trophic Levels

1. GLOBEC
The focus in this program is on invertebrate and vertebrate indicator species, as well as on the physics that influence population dynamics of animal and predator/prey interactions.
2. AMLR
The emphasis here is on the study of the functional relationships between krill, their food base, their predators and key environmental variables.
3. CEMP
The focus of CEMP is on off-shelf populations of invertebrates and vertebrates, and on the relation of Antarctic marine living resources with each other and with their physical environment.

C. Upper Trophic Levels

1. APIS
The program focuses on the ecological importance of pack-ice seals in the Antarctic marine ecosystem.

II. LONG-TERM PROGRAMS (>10 YEARS)

1. LTER

   Emphasis in this program is on interannual variability in the annual extent of pack-ice and its influence on the marine ecosystem.

2. LMR-GOOS

   The program main focus is on monitoring and predicting the state of the marine ecosystem at regional and global scales.

3. GLOCHANT

   This long-term program is set up to address broad interdisciplinary topics which are central to global change studies.

5. Relationships/Overlap Among the Antarctic Programs

JGOFS, which focuses on CO_2 and primary production, is concerned with off-shelf (water column) processes, physics, measurement of CO_2 and primary production. On the other hand, SO-GLOBEC, which was developed to complement SO-JGOFS, is concerned with off-shelf processes, invertebrates and vertebrate indicator species, as well as the physics that influences the population dynamics of animals and predator/prey interactions. Both SO-JGOFS and SO-GLOBEC include strong modeling components.

CEMP is concerned with off-shelf populations of invertebrates and vertebrates and has a management focus. It has much in common with SO-GLOBEC in as much as they are monitoring the same species.

LMR-GOOS concept is closely related to that of GLOBEC, as the GLOBEC mission is to advance our understanding of precisely those features of the marine ecosystem which LMR-GOOS aims to monitor and predict.

Whereas APIS is concerned with populations of crabeater seals that live out of the ice edge, CS-EASIZ is concerned with both benthic and pelagic indicator species (their population structure and dynamics) as influenced by sea ice. However, both APIS and CS-EASIZ are highly complementary in terms of the potential for both scientific and logistical coordination.

6. Conclusions: Where To From Here ?

The wealth of information on the physics, chemistry and biology of the Southern Ocean gained from the BIOMASS, JGOFS, GLOBEC, AMLR, AMERIEZ and CCAMLR Programs, has significantly advanced our understanding of the ecology of the Southern Ocean. The information gathered from these programs indicates that the pelagic ecosystem is far more complex than previously assumed. For instance, the AMERIEZ Program has shown that pack-ice is far from being an inhospitable environment, rather it has emerged as an important winter refuge in the life cycles of many pelagic organisms including krill. Further, in addition to krill, copepods and salps are now recognized as important grazers in the water column.

Despite the valuable information that has been accumulated on the Southern Ocean, there are conspicuous gaps in our knowledge that need to be addressed. For instance, there are still considerable uncertainties about the magnitude of primary production of the Southern Ocean and an explanation of the factors which govern phytoplankton distribution and production continues to defy scientific inquiry. And notwithstanding the great efforts of research during the past twenty five years, the "Antarctic Paradox", *i.e.* "High Nutrients, Low Chlorophyll (HNLC)" abstraction remains largely unresolved. Further, in spite of the extensive studies on krill distribution, abundance and population dynamics, we are still far from resolving the factors enabling the maintenance of the enormous krill stocks or the underlying mechanisms of swarm formation and dispersal. Moreover, the phytoplankton-krill distributional relationships still remain one of the most vexing problems in Antarctic marine ecosystems studies. Other gaps in our knowledge include:

- The role of sea-ice (including albedo feedback, ice-thickness, and ice-dynamics which has not been well addressed) needs to be incorporated into climate models.
- The effects of UV-B on marine biota (not only phytoplankton as is currently the case) and biogeochemical processes which must be taken into account for a realistic assessment of the role of these processes in environmental changes.
- Prior to Palmer LTER, there were few systematic long-term, large-scale studies in Antarctica that would allow one to distinguish secular trends from seasonal/annual cycles and to evaluate interannual variability inherent in the system.
- The possible impact of changes in world climate as a result of increases in "greenhouse gases" and the effect these changes have on the structure and function of sea-ice and the pelagic marine ecosystems of the Southern Ocean need to be carefully assessed (Knox, 1994).
- The availability of models for any part of the Antarctic pelagic system is poor. For instance, to date, models that treat primary production processes, pelagic and sea-ice are unavailable, although some are now in development (GLOBEC, 1996) *e.g.* modeling the impact of sea-ice on the development of phytoplankton. Similarly, models for higher trophic levels are few; examples include a modeling study for the early life stages of krill (Hofmann *et al.*, 1992). Further, models need to be developed for older krill life stages, other zooplankters and top predators. Thus SO-JGOFS and SO-GLOBEC which include strong modeling components, could make a major contribution to modeling and towards a better understanding of the Antarctic marine ecosystem.

The magnitude of these problems together with the wide gaps in our knowledge of the Southern Ocean outlined above could best be tackled through international collaboration and cooperation among countries interested in the study of the ecology of the Southern Ocean. The pioneering effort of the successful BIOMASS Program has underscored the value and utility of the "internationalization" of Antarctic science. This effort needs to be emulated by such programs as SO-JGOFS, SO-GLOBEC, GLOCHANT and APIS. Unfortunately, however, while many share complementary interests, current research programs dealing with the Southern Ocean are conspicuously lacking in coordination. For instance, one notes that research programs dealing with top predators have been generally conducted independently of studies of lower trophic levels (although attempts are now underway to integrate studies of plankton ecology with those of their predators). Thus it would be highly desirable and beneficial for current research programs to establish close contact with each other, and where possible, coordinate their research activities especially if they share common objectives. The challenge now facing Antarctic scientists is to draw up an overarching, internationally coordinated, multidisciplinary research program (*sensu* BIOMASS) that integrates both the sea-ice and the pelagic zones. Such a program will need to address the wide gaps in our knowledge mentioned above (and undoubtedly many others); by so doing, it will contribute to a much better understanding of the functioning of the Antarctic marine ecosystem than we now have.

References

AZAM, F., FENCHEL, T., FIELD, J.G., GRAY, J.S., MEYER-REIL, L.A. and THINGSTAD, F. (1983): The ecological role of water column microbes in the sea. Mar. Ecol. Prog. Ser., **10**, 257–263.

AZAM, R., SMITH, D.C. and HOLLIBAUGH, J.T. (1991): The role of the microbial loop in Antarctic pelagic ecosystems. Polar Biol., **10**, 239–244.

BRINTON, E., HUNTLEY, M. and TOWNSEND, A.W. (1986): Larvae of *Euphausia superba* in the Scotia Sea and Bransfield Strait in March 1984–Development and abundance compared with 1981 larvae. Polar Biol., **5**, 221–234.

CROXALL, J.P. (1994): BIOMASS-CCAMLR relations: past, present and future. Southern Ocean Ecology: the BIOMASS Perspective, ed. by S.Z. EL-SAYED. Cambridge, Cambridge Univ. Press, 339–353.

EL-SAYED, S.Z., ed. (1977): Biological Investigations Of Marine Antarctic Systems and Stocks (BIOMASS), Vol. I. Research proposals prepared by SCAR/SCOR Group of Specialists on Living Resources of the Southern Ocean. Cambridge, Scott Polar Res. Inst., 222 p.

EL-SAYED, S.Z. (1987): Biological productivity of Antarctic waters: Present paradoxes and emerging paradigms. Antarctic Aquatic Biology, ed. by S.Z. EL-SAYED and A.P. TOMO. Cambridge, SCAR, 1–21 (BIOMASS Sci. Ser., 7).

EL-SAYED, S.Z. (1994): History, organization and accomplishments of the BIOMASS Programme. Southern Ocean Ecology: the BIOMASS Perspective, ed. by S.Z. EL-SAYED. Cambridge, Cambridge Univ. Press, 1–8.

EL-SAYED, S.Z., VAN DIJKEN, G.L. and GONZALEZ-RODAS, G. (1996): Effects of ultraviolet radiation on marine ecosystems. Int. J. Environ. Stud., **51**, 199–216.

EXERSON, I. and MILLER, D.G.M. (1994): Krill mesoscale distribution and abundance: Results and implications of research during the BIOMASS Program, Southern Ocean Ecology: the BIOMASS Perspective, ed. by S.Z. EL-SAYED. Cambridge, Cambridge Univ. Press, 129–143.

FAY, R. (1973): Significance of nanoplankton in primary production of the Ross Sea, Antarctica, during the 1972 austral summer. Ph.D. dissertation, Texas A&M University, 184 p.

GLOBEC (1994): Southern Ocean Implementation Plan. Report of the Second Meeting of an International GLOBEC Working Group, Bremerhaven, Germany, June 6–8, 1994, 42 p.

HART, T.J. (1942): Phytoplankton periodicity in Antarctic surface waters. Discovery Rep., **21**, 261–356.

HASLE, G.R. (1969): An analysis of the phytoplankton of the Pacific Southern Ocean: abundance, composition, and distribution during the *Brategg* expedition, 1947–1948. Hvalrad Skr., **52**, 1–168.

HEMPEL, I., HEMPEL, G. and Baker, A.de C. (1979): Early life history stages of krill (*Euphausia superba*) in Bransfield Strait and Weddell Sea. Meeresforschung, **27**, 267–281.

HEWES, C.D., HOLM-HANSEN, O. and SAKSHAUG, E. (1985): Alternate carbon pathways at lower-trophic levels in the Antarctic food-web. Antarctic Nutrient Cycles and Food Webs, ed. by W.R. SIEGFRIED *et al.* Berlin, Springer, 277–283.

HEWES, C.D., SAKSHAUG, E., HOLM-HANSEN, O. and REID, F.M.H. (1990): Microbial autotrophic and heterotrophic eucaryotes in Antarctic waters: Relationships between biomass, CHL, ATP and POC. Mar. Ecol. Prog. Ser, **63**, 27–35.

HOFMANN, E.E., CAPELLA, J.E., ROSS, R.M. and QUETIN, L.B. (1992): Models of the early life history of *Euphausia superba* - Part I. Time and temperature dependence during the descent-ascent cycle.

Deep-Sea Res., **39**, 1177–1200.

HOFMANN, E.E., ROSS, R.M. and QUETIN, L.B., ed. (1996): Foundations for Ecological Research West of the Antarctic Peninsula. Washington, D.C., Am. Geophys. Union, 448 p. (Antarctic Research Series, **70**).

HOLT, R.S., HEWITT, R.P. and ROSENBERG, J.E. (1991): The U.S. AMLR program: 1990–1991 field season activities. Antarct. J. U.S., **26** (5), 187–188.

IOC (1996): Towards Operational Oceanography: The Global Ocean Observing System (GOOS). IOC/INF-1028.

IWC (1996): Report of the IWC Workshop on Climate Change and Cetaceans. Hawaii, U.S.A, March 25–30, 1996, 26 p.

KARL, D.M. (1991): RACER: Research on Antarctic Coastal Ecosystem Rates. Preface. Deep-Sea Res., **38** (8/9), v-vii.

KARL, D.M., HOLM-HANSEN, O., TAYLOR, G.T., TIEN, G. and BIRD, D.F. (1991): Microbial biomass and productivity in the western Bransfield Strait, Antarctica, during the 1986–1987 austral summer. Deep-Sea Res., **38**, 1029–1055.

KNOX, G.A. (1994): The Biology of the Southern Ocean. Cambridge, Cambridge Univ. Press, 444 p.

ROSS, R. and QUETIN, L. (1982): *Euphausia superba*: Fecundity and physiological ecology of its eggs and larvae. Antarct. J. U.S., **17** (5), 166–167.

SCAR (1994): Coastal and shelf ecology of the Antarctic sea-ice zone: Science plan and implementation plan. SCAR Rep., **10**, 20 p.

SCAR (1996): Report of the fourth meeting of the Group of Specialists (GLOCHANT IV), held at the University of Wisconsin, Madison, Wisconsin, U.S.A., April 10–14, 1996, 16–26.

SCOR (1992): Joint Global Ocean Flux Study: Southern Ocean Study. JGOFS Rep., **10**, 32 P.

SCOR (1996): Report of the Planning Workshop for the Living Marine Resources Module of the Global Observing System. University of Massachusetts, Dartmouth, Mass., U.S.A., March 1–5, 1996.

SULLIVAN, C.W. and AINLEY, D.G. (1987): AMERIEZ 1986: A summary of activities on board the R/V *Melville* and USCGC *Glacier*. Antarct. J. U.S., **22** (5), 167–169.

VON BROCKEL, K. (1981): The importance of nanoplankton within the pelagic Antarctic ecosystem. Kieler Meeresforsch. Sonderh., **5**, 61–67.

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